SEP 13 1926

Volume 12 Number 4

Journal of the Optical Society of America and Review of Scientific Instruments

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Published Monthly by the
OPTICAL SOCIETY OF AMERICA

OFFICE OF PUBLICATION
GEORGE BANTA PUBLISHING COMPANY
450-454 Ahnaip St.,
MENASHA, WISCONSIN

Entered as second-class matter May 31, 1921, at the postoffice at Menasha, Wis., under the Act of March 3, 1879. Acceptance for mailing at special rate of postage provided for in the Act of February 28, 1925, embodied in paragraph 4, section 412, P. L. and R. authorized June 19, 1925.

Journal
of the
Optical Society of America
and
Review of Scientific Instruments

Published monthly by the Optical Society of America in cooperation with the Association of Scientific Apparatus Makers of the United States of America. The Section on Optics is devoted to original papers on experimental, theoretical, and applied optics. The Section on Scientific Instruments is devoted to original papers on instruments of all kinds (electrical, mechanical, thermal, etc. as well as optical) for research, instruction, and industrial processes. Manuscripts for publication are invited, whether authors are members of the Optical Society or not.

Annual subscription $5.00, dating from January of current year. Single copies $0.60. Back numbers: Vols. 1-5 (The Journal of the Optical Society, 1917–1921 inclusive) $16.00. Vol. 6–7, $5.00 per volume; Vol. 8—, $2.50 per volume. "Address publishers, George Banta Publishing Company, 450–454 Ahnaip Street, Menasha, Wisconsin, or F. K. Richtmyer, Manager, Cornell University, Ithaca, New York, for all correspondence regarding subscriptions, back numbers, changes of address, advertising rates and accounts, and missing numbers."

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Journal
of the
Optical Society of America
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Vol. 12 APRIL, 1926 Number 4

THE FUNDAMENTALS OF GLARE AND VISIBILITY

By L. L. Holladay*

ABSTRACT

A résumé is presented of the results obtained in an extensive research into the many ways in which glare affects visibility.

Visibility was studied chiefly by the method of least perceptible contrasts of brightnesses. Results are presented showing the influence of adaptation and of form and size of test-object upon contrast sensitivity.

The results of the investigation show that the least perceptible brightness-difference between an object and its background increases directly with the illumination at the eye from the dazzle-source; varies approximately inversely with the square of the angle which the glare-source makes with the line of vision; and is practically independent of the brightness, size, type, distance, etc. of the dazzle-source.

Considerable study has been given to the variations of the pupil under steady, fluctuating, and glaring lights and of their influence upon vision. Results of the investigations upon irradiation, after-images, blinding-glare and light-shocks are also presented.

SYMBOLS AND TERMS

The following symbols are employed throughout this paper:

A = apparent increase of the visual angle in minutes of a bright strip viewed against a dark background; or conversely, it is the apparent decrease of visual angle in minutes of a dark strip seen against a bright background.

B = brightness in millilamberts of a light-source in the field of view of an observer.

B_1 = veiling-brightness in millilamberts.

B_2 = brightness in millilamberts of the background of the test-object in the study of irradiation.

d = visual angle in minutes subtended by a given test-object.

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D = angle in degrees between the line of vision of an observer and a line drawn from his eye to the center of the dazzle-source.

E = number of lux or meter-candles of unidirectional illumination at the eyes of the observer from a light-source in his field of view.

f = diffuse reflection-factor of the test-object.

f_1 = diffuse reflection-factor of the background of the test-object or of its surrounding field.

F = brightness in millilamberts of the background and field surrounding the test-object, or of the field to which the eyes are adapted.

F_0 = initial brightness in millilamberts of the adaptation or general field of view employed in the study of pupillary changes.

F' = brightness in millilamberts of the general field of view after it has been momentarily increased from its initial brightness.

F_1 = apparent brightness in millilamberts of the background of the test-object as observed through a sheet of plate glass between the eyes of the observer and the test-object.

K = logarithmic constant expressing the magnitude of the "psychophysiological sensation" of a light momentarily exposed to view.

P = the observed diameter of the pupil of the eye in millimeters.

P_0 = the diameter of the pupil of the eye in millimeters corresponding to the initial brightness F_0 of the adaptation field.

P' = the diameter of the pupil of the eye in millimeters after an increase in illumination.

Q = solid angle in steradians subtended at the eyes of an observer by a light-source of a square centimeters of projected area placed at a distance of r centimeters from his eyes, or $Q = a/r^2$ approximately.

R = distance in centimeters between the eyes of an observer and a test-object upon which the observer's eyes are fixated.

S = contrast sensitivity of an observer's eyes measured by the ratio of the brightness of the background of a test-object to the minimal difference in brightness between the test-object and its background when it is just visible or just not visible.

t = transmission factor of a plate glass reflector or other medium between the eyes and the test-object.

T_0 = the time in seconds the eyes are exposed to a light-source in the center of the visual field.

T = the time in seconds since the end of an exposure of the eyes to a light-source.

One millilambert (ml) is the average brightness of a perfectly reflecting and diffusing surface having an illumination of 10 meter-candles or 0.93 foot-candles. Or one millilambert is the average brightness of

a surface having a diffuse reflection-factor of 0.93 and an illumination of one foot-candle.

All logarithms are expressed in the Common System in which 10 is the base.

VEILING-BRIGHTNESS AND CONTRAST SENSITIVITY

Veiling-brightness is the density of a more or less uniformly distributed flux of light from extraneous objects and sources shining into the eyes. This extraneous light being more or less uniformly distributed, intermingles with the light from the object viewed and its surroundings in such a way as to apparently increase their respective brightnesses

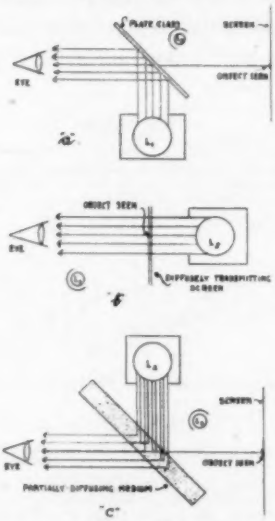

FIG. 1. *Illustrating various sources of veiling-brightness: a,* by reflection; *b,* by transmission; *c,* by scattering or diffusion.

without increasing their actual difference of brightness. This results in a loss of contrast between the object and its background, since the eye is more sensible of relative than of absolute brightnesses.

Veiling-brightnesses may arise from reflection, transmission, diffusion or scattering of light from our surroundings as illustrated in Fig. 1. We are all familiar with the reflection of veiling-brightness from shiny desk tops, glossy paper, tops of show cases, glass of show windows, wet streets, and gloss or glass over pictures. Veiling-brightness by transmission is experienced when we attempt to read print upon a thin sheet of paper with light traversing it from the underside. Veiling-

brightness by diffusion and scattering of light may arise from illuminated fog or dust, from soil and particles on one's eye glasses, from the shield of his automobile, etc.

Influence of Adaptation upon Contrast Sensitivity. In the investigation of the effect of veiling-brightness upon vision, a study was made of the influence of adaptation upon the contrast sensitivity of the eye when various forms of test-objects were employed. A diagram of the apparatus employed is shown in Fig. 2. The observer was placed at a distance of 344 cm from a screen upon which the test-object was placed. The screen had a reflection-factor $f_1=0.75$, and was illuminated to a brightness F by shaded tungsten filament lamps L_2 and L_3. A veiling-brightness B_1 was reflected into the eyes of the observer by a plate glass

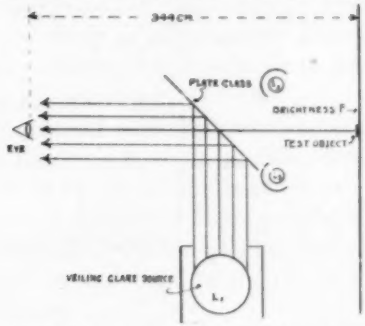

FIG. 2. *Arrangement of apparatus used in investigating veiling-brightness.*

reflector. The source L_1 of the veiling-brightness was a tungsten filament lamp enclosed in a 10 or 12-inch white diffusing spherical ball. Owing to the interposition of the plate glass reflector, whose transmission $t=0.9$, the density of light flux F_1 traversing the plate glass reflector from the test-object was $F_1=0.9F$. Therefore the total flux density from the direction of the screen was the component F_1 from the screen, plus the veiling component B_1 which was reflected from the plate glass reflector, or

$$\text{total brightness}=F_1+B_1 \quad , \qquad (1)$$

The reflection-factor of the test-object was f, and therefore its brightness was fF/f_1. The difference in brightness between the test-object and its background was $F-(fF/f_1)$, and the portion traversing the plate glass was about 0.9 thereof. Therefore the observed difference in brightness, ΔF_1, between the test-object and its background was

$$\Delta F_1=0.9\frac{f_1-f}{f_1}F \qquad (2)$$

Since the contrast sensitivity S of the observer's eyes for a given test-object is the ratio of the total brightness F_1+B_1 to the minimal difference in brightness ΔF_1 at which the test-object could just be seen or just not seen, the contrast sensitivity therefore becomes

$$\text{contrast sensitivity, } S=\frac{F_1+B_1}{\Delta F_1} \tag{3}$$

The test-objects used in this investigation were cut out of matt gray papers and pasted on a white dull-finished bond paper background having a reflection-factor $f_1=0.75$. The forms of test-objects employed are shown in Fig. 3. It may be noted here that with the test-object at the distance of 344 cm, the transverse or radial width of the test-object expressed in millimeters is numerically the same as the visual angle in minutes it subtends.

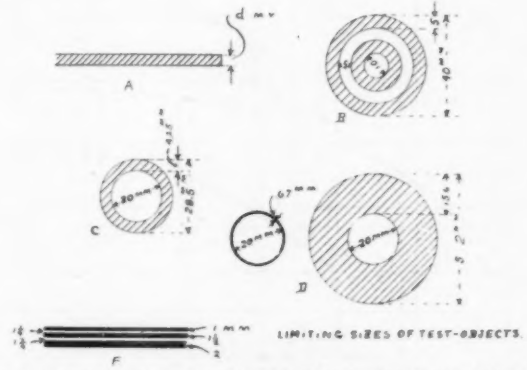

FIG. 3. *Forms of test-objects employed in investigating glare and visibility.*

In making an observation with a given test-object either the veiling-brightness B_1 is adjusted and the illumination upon the test-object varied until it is just invisible, or else the brightness F of the background of the test-object is adjusted and the veiling-brightness B_1 varied until the test-object is just visible or just invisible. The first method is preferred because of the more satisfactory adaptation, since the veiling-brightness B_1 is generally much larger than the brightness of the screen.

In Fig. 4 are shown the variations of contrast sensitivity S, for various total or adaptive brightnesses, F_1+B_1, for each form of test-object. In curves *a* and *b*, Fig. 4, are plotted the values of S obtained with one observer when using a form of test-object, shown at A in Fig. 3, consisting of a strip of gray paper of indefinite length and 1.1 and 4.1 mm

wide respectively and having a reflection-factor $f=0.52$, (the reflection-factor f_1 of the background being 0.75). Since the test-object was at the distance of 344 cm, the widths of the test-objects subtended visual angles d of 1.1 and 4.1 minutes respectively. In curve C, Fig. 4, are plotted the values of S obtained with two observers when using the form of test-object shown at B in Fig. 3 and consisting of two concentric annuli each of 5 mm radial width and subtending visual angles of 5 minutes. The reflection-factors f of the test-object varied from 0.04 to 0.7. In curve d, Fig. 4, are plotted the values of S obtained with four observers when using a test-object consisting of an annular ring of radial width subtending a visual angle d of 4.25 minutes. The reflection-factor f of the test-object was 0.47.

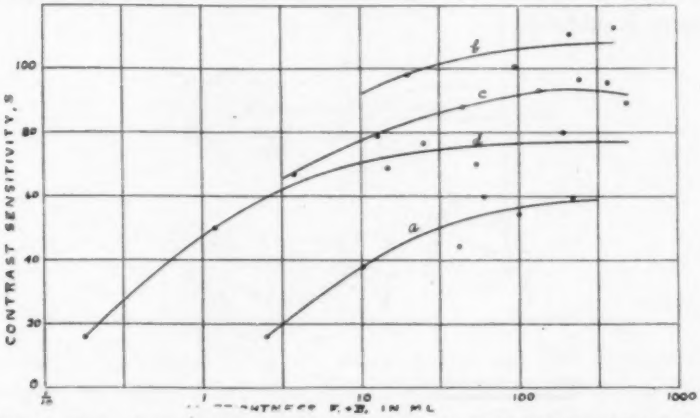

FIG. 4. *Curves showing variation of contrast sensitivity S with total brightness F_1+B_1 in ml for various test-objects: a*, with test-object shown at *A* in Fig. 3 when visual angle $d=1.1$ min.; *b*, with test-object *A* when $d=4.1$ min.; *c*, with test-object *B* when $d=5$ min., and *d*, with test-object *C* when $d=4.25$ min.

From these curves it appears that the contrast sensitivity S of the human eye (that is its ability to distinguish small differences in brightness) attains practically a maximum for total brightnesses, F_1+B_1, between 10 and 25 ml. This value of contrast sensitivity for approximately optimum total brightnesses we designate by Sm.

In Fig. 5 is shown how the contrast sensitivity varies with total apparent brightness, F_1+B_1, for an observer when using different colored lights and employing the test-object shown at C in Fig. 3. The radial width of the annulus of the test-object subtended a visual angle of 4.25 minutes; and the gray paper annulus had a reflection-factor

$f=0.47$. Curve *a*, Fig. 5, shows values of S for light of the color of the north sky from a Mazda C_3 photographic blue lamp. Curve *b* shows values of S for light from an ordinary Mazda C_1 lamp; and curve *c* shows values of S from a deep signal-colored red light. It may be noted that for light from the Mazda C_1 and C_3 lamps the average contrast sen-

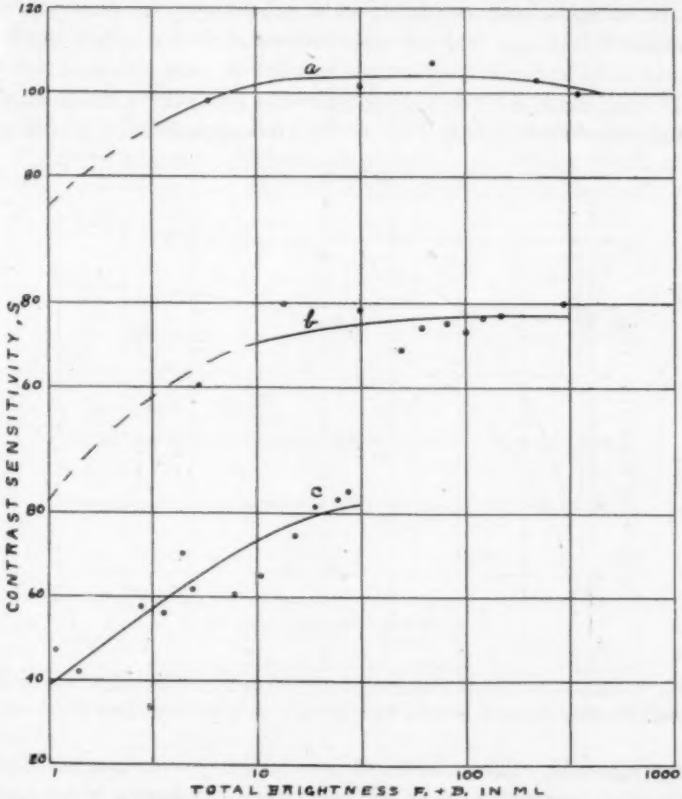

FIG. 5. *Curves showing variation of contrast sensitivity S with total brightness, for different colored lights, when using test-object C: a*, with photographic blue light; *b*, with Mazda C_1 light; and *C*, with red light.

sitivity was practically constant for total apparent brightnesses greater than 10 to 20 ml; and that for red light, the contrast sensitivity increased with increasing total brightnesses, F_1+B_1, until it reached a probable maximum at about 20 ml. It may also be noted that the contrast sensitivity for the photographic blue light was greater than for lights containing greater proportions of red light.

Influence of Visual Angle upon Contrast Sensitivity. A study was also made of the influence of the visual angle of each form of test-object upon the contrast sensitivity of the eye. Curves *a*, Figs. 6 and 7, show the variation of contrast sensitivities *Sm* (for total brightnesses of 20 ml or more) with the visual angle *d* of the test-object. The observer used a form of test-object consisting of a narrow strip of gray paper as shown at *A* in Fig. 3. The reflection-factor *f* of the test-object was 0.52. Curves *b*, Figs. 6 and 7, show the variation of contrast sensitivity *Sm* with visual angle *d* for four observers when using the annular form of test-object shown at *D* in Fig. 3. The reflection-factor *f* of the test-

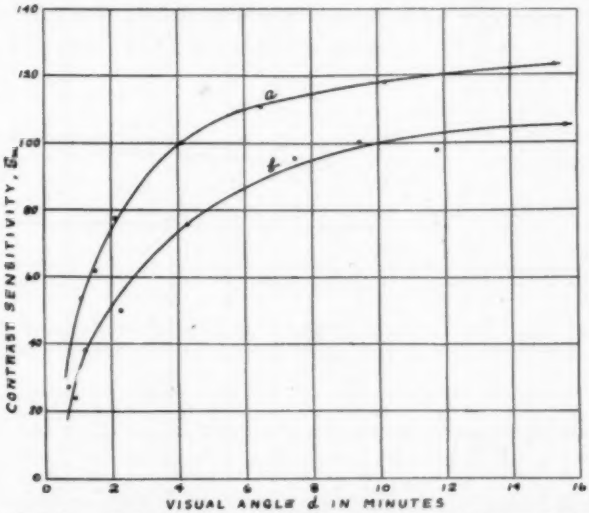

FIG. 6. *Showing variation of contrast sensitivity* S_m *(for total brightnesses* F_1+B_1 *of 20 ml or more), with visual angle d in min.: a,* with test-object *A*; *b,* with test-object *D.*

object was 0.47. These curves show a tendency to attain practically a maximum for visual angles *d* between 10 and 15 minutes, which means that with these forms of test object the one whose visual angle *d* is about 10 minutes is most easily visible. From Fig. 7 it appears that for visual angles *d* between 0.7 and 10 minutes the values of contrast sensitivity for total brightnesses of 20 ml or more are fairly well satisfied by the empirical equation.

$$\text{Contrast sensitivity, } Sm \propto (d-0.5)^{0.4} \qquad (4)$$

Variation of Ease of Vision with Brightness Contrast. In order to see an object with ease, comfort and certainty the brightness difference

between the object and its background must be greater than the minimal or threshold value at which it may just be seen; that is, the contrast of brightnesses must be greater than the least perceptible. If when an object is more or less readily seen as under ordinary circumstances there is a difference of brightness between the test-object and its background of ΔF and the minimum perceptible difference is ΔF_T then the ratio of actual difference to the minimum perceptible difference is $\Delta F/\Delta F_T$ and is some measure of the visibility of the object.

It has been found for a test-object of the form shown at *D* in Fig. 3 and having a visual angle *d* of 5 minutes and seen with the eyes adapted to an optimum total brightness that when $\Delta F/\Delta F_T = 1$ the object is just invisible; but when it is equal to 3 the object can be seen only with

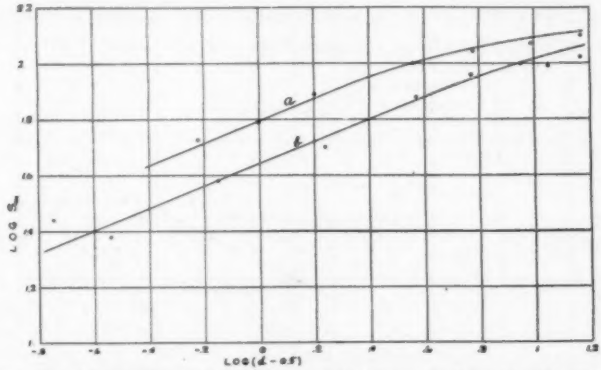

FIG. 7. *Showing approximate straight line relationship between log S_m and log $(d-0.5)$: a,* with test-object *A*; *b,* with test-object *D*.

great difficulty; when it is equal to 10, vision of the object is quite appreciably impaired; and when it is 20 or more vision is only noticeably impaired.

It appears that the ease and possibly the certainty of seeing a given object varies somewhat as the logarithm of $\Delta F/\Delta F_T$ or

$$\text{ease of seeing} \propto \log (\Delta F/\Delta F_T)$$

This relation is illustrated in Fig. 8.

DAZZLE-GLARE

Dazzle-glare is the term applied to that class of phenomena associated with bright lights in the field of view which form images upon peripheral portions of the retina and which in one way or another reduce the sensitivity of the eye for seeing objects imaged upon the central or

foveal region of the retina. Some familiar examples of lights producing this type of glare are the sun, headlights of approaching automobiles, street arc lamps, wall-brackets or ceiling lights, and unshaded lamps over our desk or workbench.

The chief ill effects of dazzle-sources shining into the eyes are decrease of the ability of the eye to perceive brightness differences, and the production of nervous strains. These effects at times are slight and only noticeable, when long continued, and at other times so severe as to render vision almost impossible, and produce nervous strains that are very injurious and well nigh unbearable.

An outstanding difficulty in a study of the phenomena has been a lack of knowledge as to its source,—whether physical, physiological, or

FIG. 8. *Diagram illustrating ease of seeing with various contrasts of brightness between test-object and background.*

psychological, that is, whether the seat of the trouble was in the media of the eye, the retina, the brain or in all of them. Therefore the problem has been attacked from many sides with the result that many variables have been discovered and their actions studied; however, their interdependence has in instances rendered their exact determination difficult or uncertain.

The factors involved in the problem may be classed either as objective or subjective. The objective factors are:

(1) Candlepower of source, brightness, dimensions, color, type, distance of source from the eyes of the observer, magnitude and direction of the angle between the source and the line of vision.

(2) Form, size, distance, and reflection-factor of test-object.

(3) Brightness of screen and its contrast with the test-object. The subjective factors involved are: adaptation, pupillary aperture, accommodation, contrast sensitivity of the observer's eye, variations between individuals.

Influence of Illumination at Eye from Dazzle-Source. In the study of the influence of the amount of illumination at the eye from the dazzle-source, an arrangement of apparatus was employed similar to that shown in Fig. 9. The observer was seated so that his eyes were 344 cm from the screen on which the test-object was placed. The screen had a reflection-factor $f_1 = 0.75$ and was illuminated to a brightness of F ml by shaded tungsten filament lamps L_2. The dazzle-source L_1 consisted of a tungsten filament lamp enclosed in a 10 or 12-inch white diffusing ball. Over the front of the box enclosing it was placed a cardboard disk

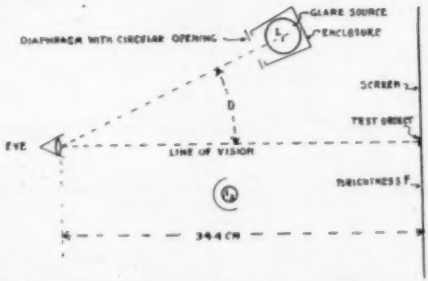

FIG. 9. *Arrangement of apparatus used in investigating dazzle-glare.*

in which a circular opening was cut. By using disks with various sized openings any desired area of the globe could be projected to the view of the observer. The dazzle-source was so placed that while the observer was viewing the test-object a line drawn from his eyes to the center of the projected area of the dazzle-source made an angle of D degrees with the observer's line of vision.

The forms of test-object employed throughout this investigation are shown in Fig. 3. The test-objects were cut from gray paper which had a reflection-factor of f and were pasted upon a background of white bond paper having a reflection-factor f_1 of 0.75.

In making an observation the dazzle-source was placed at such a distance above the test-object as to subtend an angle therewith of D degrees; and was adjusted to give E meter-candles at the eyes of the observer; then the illumination upon the screen was varied until the difference in brightness between the test-object and its background

was the least at which the test-object was perceptible. Under these conditions the brightness difference between the test-object and its background was

$$\Delta F = \frac{f_1 - f}{f_1} F \tag{5}$$

When the form of test-object shown at E in Fig. 3 was placed beneath the dazzle-source with stripes running vertically and the observer viewed a point 5 degrees below the dazzle-source the data shown in curve a, Fig. 10, were obtained; and when he viewed a point 10 degrees below the center of the dazzle-source the data shown in curve b, Fig. 10,

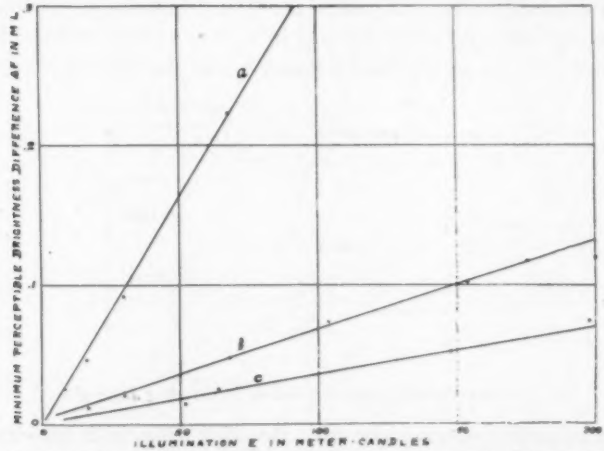

FIG. 10. *Curves showing proportionality of the minimum perceptible difference in brightness ΔF between a test-object and its background to the intensity of unidirectional illumination E from a dazzle-source: a and b,* with test-object E when dazzle-source made angles D of 5 and 10 degrees respectively with the line of vision; c, with test-object C when $D = 10.6$ degrees.

were obtained. When the test-object shown at c in Fig. 3 was used and placed at an angle of 10.6 degrees below the center of the dazzle-source the data shown plotted in curve C, Fig. 10, were obtained. From these curves it is evident that the brightness difference ΔF between the test-object and its background that was necessary in order that the given test-object be just visible at the angle D below the dazzle-source was proportional to the intensity of illumination E at the observer's eyes from the dazzle-source. Or, put a little differently, the illumination E at the eyes of an observer from a dazzle-source D degrees above his line of vision which just obscures a given test-object is proportional to

the difference in brightness ΔF between the test-object and its background, or

$E/\Delta F$ is practically constant for a given angle D.

Influence of the Angle of the Dazzle-Source. In a study of the influence of the angle that the dazzle-source makes with the line of vision upon its obscuration of the test-object, the apparatus was arranged as shown in Figs. 9 and 11.

An investigation was made with two observers using the arrangement of apparatus shown in Fig. 11 and the form of test-object shown at E in Fig. 3. As may be seen from the arrangement of apparatus, the illumination E at the observer's eyes was varied by use of the adjustable rotating sectored disk, or by varying the wattage of lamp L_1, or by using diaphragms with different sized openings. The test-object was

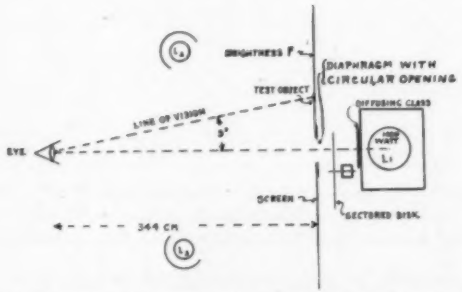

FIG. 11. *Arrangement of apparatus used in the study of dazzle-glare.*

placed to the left of the dazzle-source with its strips horizontal. The reflection-factor of the test-object was 0.31. Observations were made with diaphragms having openings of 5, 3.53 and 2.5 cm diameter which presented areas of the dazzle-source which subtened solid angles Q of 16.6×10^{-5}, 8.3×10^{-5}, and 4.15×10^{-5} steradians respectively at the eyes of the observer. A series of observations were taken with the brightness F of the screen at 1/10, 1 and 10 ml. A reading consisted in placing the proper diaphragm in front of the dazzle-source, adjusting and maintaining the brightness of the screen at F ml, adjusting the illumination at the eyes from the dazzle-source to E mc and then observing the place upon the test-object at which it became just invisible. These results are plotted in Fig. 12. Except for extremely small values of angle D it was immaterial which value of Q was used, and there was no appreciable affect upon the ratio, $E/\Delta F$, which

brightness of screen, F, was used. Therefore from the curve it appears that the data are fairly well satisfied by the empirical equation

$$E/\Delta F \propto D^{2.4}$$

A similar investigation was made upon three other observers when the dazzle-source was at an angle above the test-object. The arrangement of apparatus used is shown in Fig. 9, and the test-object employed is shown at B in Fig. 3. The dazzle-source was a 500 watt tungsten lamp in a 10-inch white diffusing ball, and its projected area subtended a solid angle Q of 8.65×10^{-3} steradians. The radial width of each

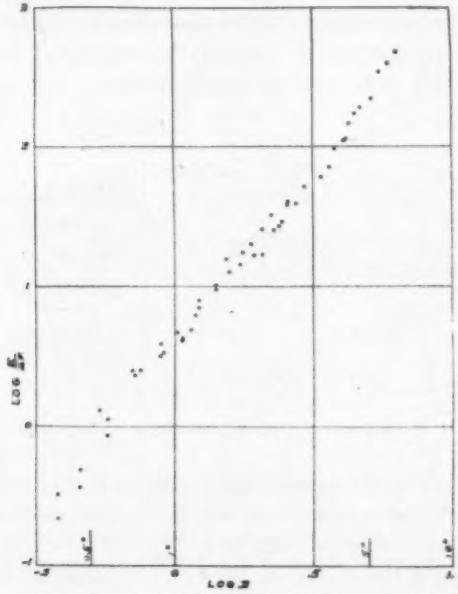

FIG. 12. *Curve showing a straight line relationship between log $E/\Delta F$ and log D.*

annulus of the test-object subtended a visual angle of 5 minutes. The reflection-factors of various test-objects used were 0.04, 0.28, 0.48, 0.52, and 0.62. In Fig. 13 are plotted an average of the results obtained with each observer. These data are fairly well satisfied by the empirical equation

$$E/\Delta F = 22.5D^2 \qquad (6)$$

Therefore the meter-candles of illumination E at the eye from the dazzle-source to obscrure the test-object per millilambert difference in brightness between the test-object and its background vary approx-

imately as the square of the angle the dazzle-source makes with the line of vision.

Analogy between Dazzle-Glare and Veiling-Brightness. Having noticed that the effect of a dazzle-source in the field of view of an observer

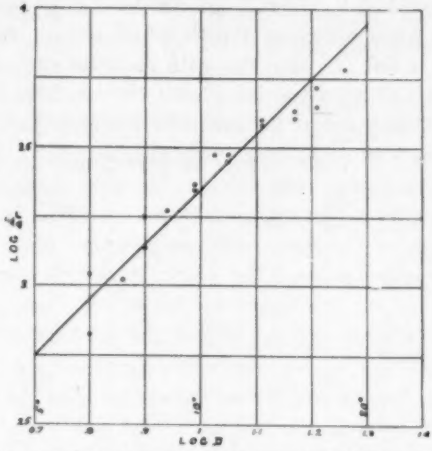

FIG. 13. *Showing that the least perceptible difference in brightness ΔF between a test-object and its background varies directly with the illumination E at the eye from the dazzle-source; and varies approximately inversely as the square of the angle D that it is elevated above the line of vision.*

seemed to be very similar to that of a veiling-brightness, it was determined to study the phenomena in a comparative manner. To do that, a test was so arranged (see Fig. 14) that a given test-object was placed

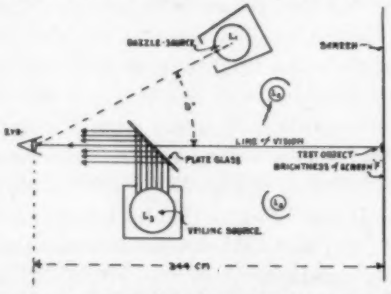

FIG. 14. *Arrangement of apparatus used in the comparative study of veiling-brightness and dazzle-glare.*

upon a screen which was illuminated and maintained at a constant brightness of F by shaded tungsten lights, L_2. Two glare-sources—L_1, a dazzle-source, and L_3, a veiling-source—were arranged so that for a

given brightness F of the screen, the obscuring illumination E of the dazzle-source could be found and then the dazzle-source turned out and the veiling-source turned on and the valve B_1 of the veiling-brightness found which gave an identical obscuring effect. The dazzle-source L_1 consisted of a 500-watt gas-filled tungsten lamp either bare or enclosed in a white diffusing 10-inch spherical ball, with its center D degrees above the line of vision and with the front enclosing cover containing an 8 inch circular opening placed 194 cm from the eyes of the observer. The veiling-source L_2 consisted of a large gas-filled tungsten lamp enclosed in a 10 or 12-inch white diffusing ball. The light from this veiling-source L_2 was reflected into the eyes of the observer along his line of vision by a plate glass reflector as shown in Fig. 14. The veiling-brightness of the light reflected from the plate glass was B_1. The transmission-factor t of the plate glass reflector between the observer's eyes and the test-object was about 0.9, therefore the brightness difference between the test-object and its background appeared to be $0.9F(f_1-f)/f_1$ or as we symbolize it, ΔF_1. The test-object as shown at B, Fig. 3, consisted of two concentric annuli of 10 and 30 mm inside diameters respectively and each of 5 mm radial widths. The reflection-factor f of the gray paper annuli of the test-object was 0.52 and the reflection-factor f_1 of the screen was 0.75.

A determination consisted in first adjusting the illumination upon the screen or background of the test-object to a brightness of F, then adjusting the illumination from the dazzle-source at the observer's eyes to such a value E that the test-object was just obscured. Next the dazzle-source was cut off and the veiling-source turned on and its brightness adjusted to just obscure the same test-object when the screen was of the same brightness as when the dazzle-source was used. The results obtained with one observer are plotted in Fig. 15. The relation of illumination E in mc from the dazzle-source to the brightness B_1 in ml from the veiling-source, which have equal obscuring effects are shown in curve a, Fig. 15. Values of $E/\Delta F_1$ are shown in curve b of Fig. 15. It may be noted that both E/B_1 and $E/\Delta F_1$ varied approximately as D^2; and also, that the contrast sensitivity, $(F_1+B_1)/\Delta F_1$ was approximately constant.

These results, together with many other similar ones, indicate that the obscuring effect of an illumination of E mc at an observer's eyes from a dazzle-source located D degrees above his line of vision are completely duplicated by a veiling-brightness of B_1 ml. They also show a close analogy between the two phenomena and suggest that

fundamentally they have a common origin. By definition the contrast sensitivity of an observer's eye to a total brightness of F_1+B_1 is

$$\text{contrast sensitivity}, S=(F_1+B_1)/\Delta F_1$$

Now since dazzle-glare has an experimental equivalence of veiling-brightness in obscuring vision, we may postulate that it has a mathematical equivalence of B_1 in the expression for contrast sensitivity, involving a function of E, D, etc. When assuming, as determined above, that $B_1 \propto E/D^2$ approximately we obtain,

$$\text{contrast sensitivity}, S=\frac{F+K_1(E/D^2)}{\Delta F} \qquad (7)$$

where K_1 is a constant having an average value of $4.3 \pm .5$.

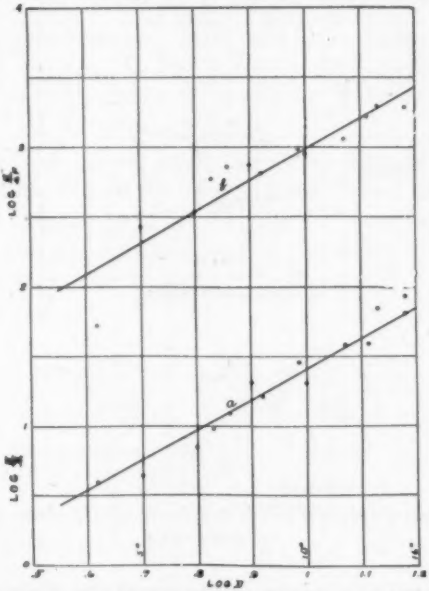

FIG. 15. *Curve a shows the variation with angle D of the ratio of illumination E from the dazzle-source to the veiling-brightness B_1 having an equal obscuring effect; curve b shows relation of $E/\Delta F$ to D.*

Solving for ΔF in the last equation we have,

$$\Delta F=F/S+(K_1/S)(E/D^2) \qquad (8)$$

which shows that the least difference in brightness ΔF between the test-object and its background at which the test object can just be seen consists of two parts; the first, F/S, which would be required were there no dazzle-glare; and the other, $(K_1/S)(E/D^2)$, which is proportional to the illumination at the eye from the dazzle-source, and varies in-

versely as the square of the angle D it makes with the line of vision. It may be noted that both components of ΔF vary inversely as the contrast sensitivity S of the eye, but this is practically constant at ordinary adaptations as has been previously shown.

Influence of Position of Dazzle-Source. This investigation was made for the purpose of determining the relative glare of a dazzle-source at a fixed angle to the line of vision, but the plane containing it, the observer's eye and the test-object varied through 360 degrees.

The arrangement of apparatus employed is shown in Fig. 16, in which L_1 is the dazzle-source occupying a position in the center of the

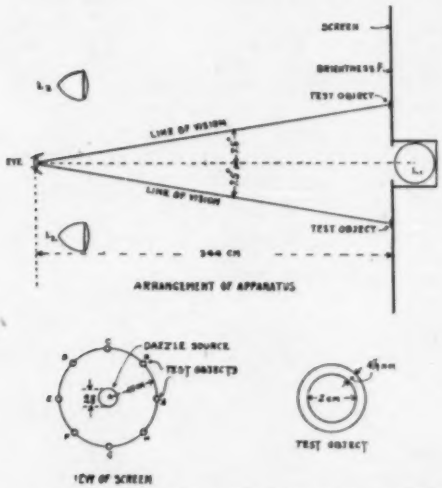

FIG. 16. *Arrangement of apparatus used in studying the effect of relative positions of test-object and dazzle-source.*

screen and located at the level of the eye of the observer. There were 8 test objects each having a reflection-factor of 0.56 and of the form shown at C in Fig. 3. These test-objects were placed symmetrically around a circle of 45 cm radius drawn about the center of the dazzle-source. The dazzle-source L_1 was a gas-filled tungsten lamp in a 10-inch white diffusing ball which gave an illumination E of 31.5 mc at the observer's eye. The results obtained with eight observers are given in Table 1 from which it is evident that the position of the dazzle-source relative to the test-object was without material effect upon its obscuring power so long as the angle D was maintained constant.

TABLE 1. *Table showing the minimum difference in brightness, ΔF, between a test-object and its background at which the test-object was seen by each observer, for various positions of the test-object, when the angle D of the dazzle-source was 7.5 degrees and its illumination E, 31.5 mc.*

Position of test-obj.	Minimum perceptible brightness difference ΔF in ml for each observer								Average
	Observer No. 1	2	3	4	5	6	7	8	$E/\Delta F$
A	.0278	.0252	.0518	.0171	.0286	.0293	.0372	.0231	1153
B	.0264	.0242	.0518	.0175	.0281	.0286	.0365	.0228	1172
C	.0269	.0252	.0494	.0171	.0274	.0312	.0367	.0242	1152
D	.0264	.0238	.0494	.0171	.0290	.0286	.0363	.0233	1174
E	.0278	.0238	.0518	.0175	.0286	.0293	.0365	.0247	1147
F	.0274	.0240	.0482	.0175	.0312	.0298	.0372	.0250	1136
G	.0264	.0230	.0482	.0171	.0286	.0293	.0365	.0242	1173
H	.0271	.0238	.0482	.0171	.0267	.0293	.0360	.0250	1172
Grand Average									1160

Additive Effects of Several Dazzle-Sources. This investigation was designed to determine how the effects of the several elements of area of an extensive dazzle-source, or the effects of two or more localized dazzle-sources, combine to give a resultant effect.

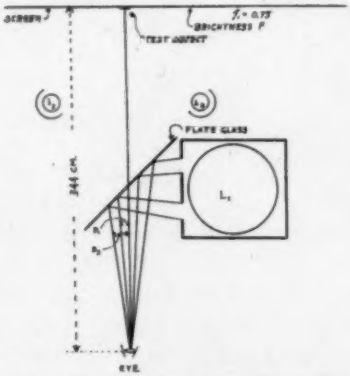

FIG. 17. *Arrangement of apparatus used in studying the effect of viewing a test-object through the center of the equivalent of an annular shaped dazzle-source.*

The first investigation was to determine the obscuring effect of a dazzle-source having a fairly extensive surface. The arrangement of apparatus was as shown in Fig. 17 in which the dazzle-source was in effect an annulus of uniform brightness through the center of which the observer viewed the test-object upon the screen 344 cm in the distance. This dazzle-annulus was formed by permitting light from

a 12-inch diffusing ball to traverse an annular opening in a disk in front of the lamp and then reflecting this light into the eyes by a plate glass reflector. The test-object had a reflection-factor of 0.47 and was of the form shown at *C* in Fig. 3. The results obtained with two observers are given in Table 2, which are comparable with results obtained by use of a single localized dazzle-source.

TABLE 2. *Showing the results obtained by viewing a test-object through the center of an annular shaped dazzle-source.*

Average brightness of background of test-object in ml	Angle, in degrees, light from edge of glare annulus makes with line of vision		Brightness of reflected light from glare annulus in ml	Apparent difference in brightness of test-object and its background	Estimated meter-candles reflected into observer's eyes	Weighted average
	Inner	Outer				
F	D_1	D_2	B	ΔF_1	E	$E/\Delta F_1$
.12	1.26	3.23	58	.041	1.56	38
.14	1.75	3.23	117	.048	2.60	54
.12	2.23	3.23	174	.041	2.90	71
.11	2.70	3.23	312	.038	2.97	78

The second method employed was to take two dazzle-sources each of which gave about the same illumination at the eyes of the observer and place them upon a circle concentric with the test-object. Determinations were made of the minimum brightness difference ΔF between the test-object and its background at which the test-object could just be seen when these dazzle-sources occupied various positions upon the circle. Readings were made with numerous values of illumination from each dazzle-source. The results showed within the limits of experimental error that their combined effect was independent of their relative positions.

Therefore we may conclude that the obscuring effects of any number of dazzle-sources are additive or that the equivalent veiling-brightness B_1 of several dazzle-sources in the field of view is the sum of that for each. Thus if dazzle-sources 1 and 2 give E_1 and E_2 meter-candles of unidirectional illumination at the observer's eyes when they are located D_1 and D_2 degrees respectively out of his line of vision, then the equivalent veiling-brightness,

$$B_1 = 4.3\frac{E_1}{D_1^2} + 4.3\frac{E_2}{D_2^2} \cdots = 4.3\sum\frac{E}{D^2} = 4.3\ \frac{10}{\pi}\sum\frac{BQ}{D^2} \qquad (9)$$

since $$E = 10BQ/\pi \qquad (10)$$

Similarly when the dazzle-source consists of a large projected area of which each element of area has a brightness of B, each element is of such an area as subtends an elementary solid angle of dQ steradians, and each element makes an angle of D degrees with the observer's line of vision; then the equivalent veiling-brightness, by integration, is,

$$B_1 = 4.3\frac{10}{\pi}\int\frac{BdQ}{D^2} \qquad (11)$$

Influence of Brightness and Dimensions of Dazzle-Sources. This investigation was made with a bare gas-filled tungsten lamp, and with a similar one enclosed in a ten-inch white diffusing globe; and its purpose was to compare the minimum perceptible brightness differences between similar test-objects and their backgrounds for equal illuminations at the eye from the respective dazzle-sources.

The arrangement of apparatus was such that the two lamps were close together near the center of the screen, and beneath each lamp was placed a column of identical test-objects spaced every 5 degrees. A removable shield was placed in front of each lamp so that but one could be exposed at a time. The test-objects were of the form shown at C in Fig. 3 and they had reflection factors $f = 0.56$. A series of observations were taken at angles between test-object and dazzle-source of 5, 10, 15, and 20 degrees with values of illumination at the eye of 6.1, 10.8, 20, and 35 meter-candles; and the minimum difference in brightness, ΔF, between test-object and background was determined in each case with each of the seven observers. The ratio of the average ΔF for the enclosed to the ΔF for the bare lamp for each of the seven observers was 0.96, 1.05, 1.08, 1.09, 1.00, 1.07, and 0.98, respectively, with a grand average of 1.03. This means that the obscuring effect per unit of illumination at the eye is, within our experimental error, independent of the brightness and dimensions of the radiating or diffusing surface of the light-source.

Influence of Color of Dazzle-Source. The purpose of this preliminary investigation was to gain some idea of the relative obscuring effects of dazzle-sources of different colors.

The arrangement of apparatus employed was as shown in Fig. 14 and the test-object was as shown at C in Fig. 3 and it had reflection-factors of 0.47 and 0.04. Three colors of light were used: first, light from an ordinary Mazda C_1 lamp in a 10-inch white diffusing ball; second, light from a photographic blue lamp in a similar diffusing ball

which gave light of practically the color of the north sky; and third, light of a very deep signal colored red which was produced by a gas-filled tungsten lamp enclosed in a 10-inch white diffusing ball which had been dipped in a red lacquer. There was but one observer and the intensities used in connection with the red light were not comparable with those used in connection with the other two. However, it appeared that the observer's contrast sensitivity was greater for the photographic blue light than for the other two. Average values of the constant K_1 given in Eq. 7 were 4.9 for the photographic blue light, 4.1 for Mazda C_1 light and 3.9 for the red light. This tends to show, though the results are not conclusive, that the greater contrast sensitivity for the photographic blue light is somewhat offset by a greater glare.

Influence of Visual Angle on Contrast Sensitivity. The influence of visual angle upon contrast sensitivity being known from a study of it

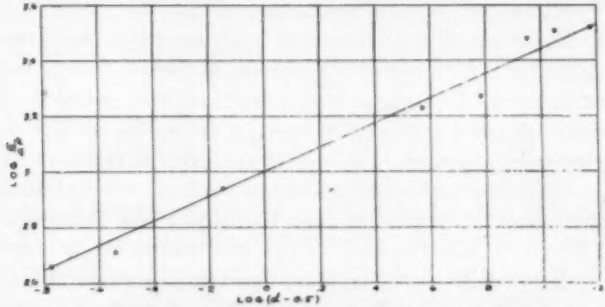

FIG. 18. *Showing a straight line relationship between log $E/\Delta F$ and log $(d-0.5)$ for test-objects, D, when the dazzle-source is elevated 10 degrees above the line of vision.*

in connection with veiling-brightness, it became interesting to see just how it would influence our results in connection with dazzle-glare.

The apparatus was arranged as shown in Fig. 9 and the form of test-object used is shown at D in Fig. 3. The test-object had a reflection-factor, f, of 0.47 and the visual angle, d, of the radial width of annulus was varied from 0.67 to 15.6 minutes. The average results obtained with two observers using the dazzle-source at an angle, D, of 10 degrees above the line of vision are shown in Fig. 18. It may be seen that $E/\Delta F$ varied approximately as $(d-.5)^{0.44}$. As this result is due to a variation of contrast sensitivity we take the average value of K_1 to be 4.3 and determine the contrast sensitivity S from Eq. 3. Therefore, neglecting the small term $f_1/(f_1-f)$, we have

$$\text{contrast sensivitity } S = 43(d-.5)^{.44} \qquad (12)$$

which is in substantial agreement with the result already found.

Influence of the Blindspot. This test was made for the purpose of determining whether the contrast sensitivity of the foveal or central vision was depressed by the image of a dazzle-source falling upon the blindspot. In making the test, a bare filament tungsten lamp was placed at an adjustable distance to the right of the test-object upon the screen; and arrangements made for varying the brightness of the screen. The observer's left eye was covered and all readings taken upon the right. Care was exercised to make sure that the dazzle-image fell upon the blindspot. Notwithstanding this precaution the observer was not unconscious of the presence of the dazzle-source for intensities of illumination E greater than 5 mc. The test-object employed is shown at C in Fig. 3; and its reflection-factor, f, was 0.56.

A qualitative test was made by first adjusting the illumination E, at the observer's eye from the dazzle-source to 20 mc and then varying the brightness of the screen until the test-object was invisible. Next, the hand was raised to shield the eye from the dazzle-source and the test-object was instantly clearly visible.

In a similar manner, measurements were made on four observers when the dazzle-image was on, just under and just over the blindspot, but there was no appreciable difference between the readings.

Influence of Accommodation. The purpose of this test was to determine what effect the accommodation of the eyes, without any change in convergence, had upon the obscuring effect of the dazzle-source. Changes in accommodation of the lenses of the eyes without changes in the convergence of the eyes was accomplished by keeping the test-object stationary and introducing lenses of various focal lengths in front of the observer's eyes. The test arrangement employed is shown in Fig. 9. The test-object used is shown at C in Fig. 3, in which $f=0.56$. The dazzle-source consisted of a 300-watt Mazda C_1 lamp in a ten inch white diffusing spherical ball. Observations were taken under two conditions, one with $D=5°$ and $E=10$ mc, and the other with $D=10°$ and $E=20$ mc. An observation consisted in placing a pair of spherical lenses in front of the observer's eyes and then with D and E constant, varying the brightness F of the screen so that the test-object just became invisible The average minimum brightness difference between test-object and background for various strengths of interposed lenses with six observers are shown plotted in Fig. 19. The results are expressed in terms of the minimum brightness difference, which occurred for most observers without the interposition of extra lenses.

Southall[3] has proved that for a given individual "all objects which have the same apparent size as measured at the principal point of the eye will produce retinal images of equal size." Therefore we may conclude that the position of the retinal image of a dazzle-source with reference to the center of the fovea is practically independent of the state of accommodation of the eye. This precludes the explanation that the increase observed above in the minimum perceptible difference was due to a change in the position of the retinal image of the dazzle-source. On the other hand, we may conclude that it was due to a loss of brightness contrast from lack of exact focus.

Influence of Pupil Diameter. This investigation was made for the purpose of determining the influence of the pupillary aperture upon the obscuring effect of illumination from a dazzle-source.

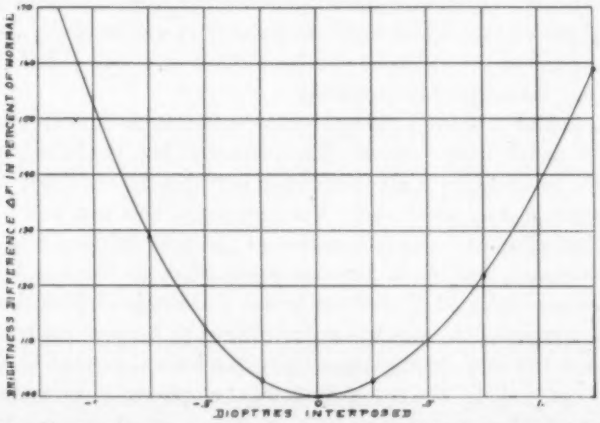

FIG. 19. *Showing the average increase of the least perceptible difference in brightness with various strengths of positive or negative spherical lenses interposed in the line of vision of an emmetropic eye.*

The arrangement of apparatus used was similar to that shown in Fig. 9, with the exception that a telescope was used for measuring the diameter of the pupil of the right eye. The telescope was so arranged that the diameter of the image of the pupil filling one-half of the field of the telescope could be compared with the image of a millimeter scale filling the other half of the field of the telescope. The dazzle-source was a large gas-filled tungsten lamp enclosed in a 10 or 12-inch white diffusing ball. The test-object was of the form *C* shown in Fig. 3.

[3] J. P. C. Southall, Mirrors, Prisms, and Lenses, p. 448.

A determination consisted first in finding the minimum perceptible brightness difference ΔF between test-object and background when the brightness of the field was F and the illumination at the eye from the dazzle-source placed D degrees above the line of vision was E; and secondly, in observing the corresponding diameter P of the pupil. An average of the values of $E/\Delta F$ plotted against corresponding values of D appear to be well satisfied by the empirical equation

$$E/\Delta F = 21D^2.$$

Now the flux of light traversing the pupil is proportional to the intensity of unidirectional illumination E and is also proportional to the effective area of the pupillary aperture. Also the retinal value of ΔF is proportional to the pupillary aperture; therefore, it appears that the effect of the aperture of the pupil would be eliminated from the above equation. However, when plotting the observed data we find it fairly well satisfied by the empirical equation

$$\frac{EP^2 \cos D_n}{\Delta F} = 370D^{1.8}$$

where D_n is the angle in degrees the beam of light traversing the pupil makes with its surface. Since this equation is less logical, more complex and fits the data no better than the former, the former is to be preferred.

Theory of Dazzle-Glare. The resultant effect of a dazzle-source shining into the eyes at an angle to the line of vision seems to be similar to that of a veiling brightness.

There are several more or less plausible explanations as to the cause or causes of the phenomenon. The seat of the phenomenon may be located in the:

(a) Brain or central nervous system.
(b) Optic nerve.
(c) Retina.
(d) Surface membranes of the eye.
(e) Media of the eye.

When any portion of the retina is stimulated, the brain receives a stimulus through the optic nerve and in turn by a reflex action described by Allen,[4] other portions of the retina of the exposed eye and of the unexposed eye are also stimulated. As to the magnitude and distribution of this reflex action over the retinas of the two eyes, we are wholly ignorant.

[4] Frank Allen, J.O.S.A. & R.S.I., p. 583; 1923.

Due to a leakage of stimulation from nerve fiber to nerve fiber in the optic nerve, another portion of the brain may become stimulated than that corresponding to the portion of the retina exposed. This phenomenon is analogous to electrolysis or to cross-talk in telephony; and of its magnitude and distribution we know nothing.

When we come to consider the retina itself as a seat of the phenomenon, we have several alternatives: When an image is formed in a peripheral portion of the retina it is conceivable that the fovea may be stimulated by a stimulus being transmitted through the fiber layers or ganglion cells from the receiving rods or cones to neighboring rods or cones and so forth, until the stimulus, (though much weakened) reaches the fovea. The exact value of the stimulus reaching the fovea undoubtedly depends upon the number and the degree of excitation of the involved cells, to the number of the transfers made or to the length of the path, to the number of transmitting parallel paths or number of alternative conducting fibers throughout the course, and to the density of cones in the fovea. As may be readily seen or shown by calculation, the stimulus reaching the fovea decreases with increasing values of the angle D that the dazzle-source makes with the line of vision. If this were the sole cause of the phenomenon it would be difficult to account for the phenomenon being observed when the dazzle-image falls upon the blindspot.

There must be a gradual change in the adaptation of the retina from the high level of brightness of the dazzle-image to the low level of brightness to which the fovea is adapted. It is believed possible that this may account in large measure for the effect, but of its modus operandi we know but little.

Light shining upon the eye may, as Cobb[5] has shown, be transmitted through the sclera, cornea and iris and be scattered over the retina. Again a portion of the light entering the pupil, may by one or more reflections at the surfaces of the lens, cornea and retina be scattered over the retina. It is probable, however, that this light is scattered more or less uniformly over the entire retina and therefore its distribution would be practically independent of the angle between the dazzle-source and the line of vision.

If the media of the normal eye are not perfectly transparent as shown by Raman[6] to be the case, a beam of light would be partially scattered. The intensity of scattered light at an angle q from the

[5] P. W. Cobb, Lectures on Ill. Eng., *2*, p. 525.
[6] C. V. Raman, Phil. Mag., *38*, p. 568; Nov., 1919.

direction of travel of a nonpolarized beam has been proved by Rayleigh[7] to be proportional to

$$I_s \propto I\left(\frac{M'-M}{M}\right)^2 \frac{mT^2}{\lambda^4}(1+\cos^2 q)\frac{1}{r^2} \qquad (13)$$

where I is intensity of the incident light; M' and M are the optical densities of the disturbing particles and the medium respectively; m, the number of particles per unit volume; T, the volume of a disturbing particle; λ, the wave-length of the scattered light; and r, the distance from the observer to the portion of beam observed.

Fig. 20 shows an eye on which the illumination is E meter-candles from a dazzle-source located D degrees out of the line of vision. Light falling upon the eye is refracted by the cornea, and that portion which

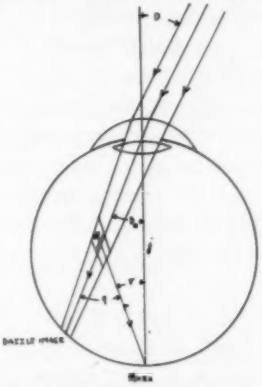

FIG. 20. *Showing a beam of light through the media of an eye where there is scattering of light from the media upon the fovea.*

enters the eye through the pupillary aperture forms a beam through the media of the eye, which makes an angle of D_n degrees with the axis of the eye.

The cross-section of the beam at the pupil is proportional to $P^2\cos D_n$, and the cross-section times the intensity I, is practically constant throughout the length of the beam; therefore the flux density upon the fovea from an element of length, dl, of the beam is

$$d\phi \propto I_s P^2 \cos D_n \cos v\, dl$$

and the total flux density upon the fovea from the dazzle-beam is $\int d\phi$. Substituting the value of E for I in the above equation and integrating we find

[7] Lord Rayleigh, Phil. Mag., *41*, pp. 107, 274, 447; 1917.

$$\int d\phi = \phi = K_2\left(\frac{M'-M}{M}\right)^2 \frac{mT^2}{\lambda^4}\,\frac{EP^2}{j}\cot D_n\left\{\cos D_n + \frac{4}{3}\cos^3 D_n - \frac{2}{3}\cos^5 D_n - \frac{\sin 2D_n}{3}(1-\sin^3 D_n)\right\} \quad (14)$$

where j is the axis diameter of the eye, K_2 a constant and the other symbols are as given above. From Eq. 14 we should expect ϕ to vary approximately as $1/D^{1.1}$ for values of D between 1 and 30 degrees.

From this last equation it is evident that the total scattered flux density upon the fovea from the dazzle-source is proportional to the number, m, of scattering particles per unit volume of the media and to the square of their volume. This is confirmed by experiment in that a dazzle-source obscures the test-object more readily the older the observer and more muddy his eyes appear. This flux density is also inversely proportional to the fourth power of the wave-length of light which is at least in the right direction as far as our experiments indicate. Also this flux density is proportional to the illumination E at the eye from the dazzle-source which is in conformity with experiment. And lastly this flux density upon the fovea is approximately proportional to the Cot D_n which is of the right general order of magnitude, but varies somewhat too slowly with the angle between the dazzle-source and the line of vision. The result is also in accord with our results when the dazzle-image falls upon the blindspot.

We have shown that a close analogy exists between dazzle-glare and veiling-brightness, and when we deduced Eq. 7 we postulated a mathematical equivalence, which may have assumed:

(1) That a dazzle-source by diffusion or otherwise casts an actual veil of light having an equivalent brightness of $4.3E/D^2$ ml or

(2) That the adaptation of the fovea was changed by the same amount as though the whole eye were flooded with a veil of light of the same amount, or

(3) That the contrast sensitivity of the eye was decreased thereby.

Our conclusion is that the dazzle-source casts an actual veil of light over the fovea or that its adaptation or sensitivity is so changed that it acts as though there were a veiling-brightness.

AFTER-IMAGES

Growth and Decay of After-Images. The purpose of this investigation was to study the growth and decay of after-images under prescribed conditions.

The arrangement of apparatus consisted of a screen placed at a distance of 344 cm from the eyes of the observer, in the center of which was a circular opening. Behind this opening was placed a gas-filled tungsten lamp which illuminated a white diffusing surface to a brightness B. A removable shield covered the opening, one portion of which was covered with black velvet and another portion with white paper. The shield was arranged so that either portion could at will be used to cover the opening. The screen had a reflection-factor $f=0.75$, and was illuminated by screened tungsten lamps to a brightness F.

A study was first made with a screen opening of 5 cm. In making a determination the eyes were adapted for a minute or more to the brightness F of the screen. Then the light-source of brightness B was exposed to view for 4 seconds after which it was covered with the velvet-coated portion of the screen. The observer having kept his eyes fixed upon the velvet coated shield, measures the time, T_1 in seconds for the brightness of the after-image to decay to the apparent brightness F of the screen. The average results obtained when using field brightness F varying from 0.06 to 100 ml are shown plotted in curve a, Fig. 21. It may be observed that the results are approximately satisfied by the empirical equation:

$$\log T_1 = 1.26 \log B - 0.31 \log F - 4.49 \qquad (15)$$

By using exactly the same arrangement of apparatus, a four second exposure, and using the velvet-coated portion of the shield to cover the glare-light, the brightness B of the glare-light was varied until for a given brightness F of the screen, the after-image appeared of the same brightness as the screen the instant the glare-light was covered. The brightness F of the screen was varied from 0.075 to 1950 ml, with a corresponding variation of B from 600 to 53 000 ml. The results thus obtained are well satisfied by the empirical equation

$$F = \left(\frac{B}{1480}\right)^4 \qquad (16)$$

By comparing this equation with the one above, it is evident that the time to make the observation must have taken about 0.3 seconds.

A similar series of observations was made on the same observers using exactly the same arrangement as above, with the exception that the portion of the shield covered with white paper was used to cover the glare-source. The exposure time was four seconds as before. In this manner the time, T_2 in seconds was measured for the apparent brightness of the after-image to decay sufficiently to be unobservable when

viewing any portion of the adapting field. These results are plotted in curve *b*, Fig. 21. The empirical equation satisfying these results is:

$$\log T_2 = 1.1 \log B - 0.31 \log F - 3.14 \qquad (17)$$

Influence of After-Images upon Discrimination. This investigation was for the purpose of determining the influence of after-images upon the ability of the eye to discriminate brightness differences.

The apparatus was arranged somewhat similar to the above in which a diffusing light-source of brightness B was placed behind a 14.5 cm opening in the center of the screen. The screen was of reflection-factor f_1, of brightness F and was placed 344 cm from the observer's eyes.

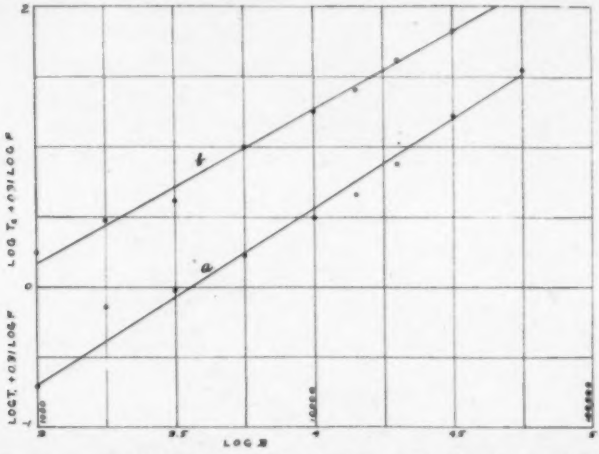

FIG. 21. *Curve a shows period of time T_1 in seconds for an after-image to decay to the apparent brightness F of the adapting field after the eyes had been preadapted to the brightness of F ml and then exposed for four seconds to a light-source of brightness B ml. Curve b shows the period of time T_2 for the after-image, similarly formed, to decay so as to be unobservable when viewing any portion of the adapting field.*

Over the opening in front of the light-source was placed a removable shield; the shield was coated on the front side with white paper of reflection-factor $f_1 = 0.75$. In the center of the shield was placed a test-object of the form shown at D in Fig. 3 in which the radial width of the test-object subtended a visual angle of 1 minute. An observation consisted in finding the number of seconds T in which the test-object was just discernible when formed by exposing the eyes for T_0 seconds to the light-source of brightness B, and decayed by viewing the white shield of brightness F, carrying the test-object. In making observations the reflection-factor f was varied from 0.04 to 0.72, the brightness F

of the screen and background was varied from 0.1 to 50 ml, and the brightness B of the light-source was varied from 450 to 11500 ml. By an analysis of the results it appeared that

$$\log T = 1.16 \log B - 0.32 \log F + 0.9 \log T_0 - 0.4 \log \frac{f_1 - f}{f_1} - 4.84 \quad (18)$$

By using the same form of test-object but varying the visual angle from 1 to 6.2 minutes, an analysis of all the data revealed the fact that within a fair degree of accuracy the effect of after-images in obscuring a test-object was similar to that of veiling-brightness. The intensity of veiling-brightness B_1 of equal obscuring effect was

$$B_1 = \left(\frac{BT_0}{yT}\right)^x$$

where x is a constant varying between 3 and 4, and y is a constant having a value of about 4000 for $x=3$, or a value of 5000 for $X=4$. Postulating, therefore, that the value of veiling-brightness B_1 in the expression for constant sensitivity S may be replaced by its experimental equivalent we have approximately

$$S = \frac{F + \left(\frac{BT_0}{5000T}\right)^4}{\frac{f_1 - f}{f_1} F} = 45(d - 0.5)^{0.4} \quad (19)$$

These equations satisfy the results fairly well between the limits of F from 1 to 50 ml, of B from 500 and 12000 ml, of T_0 from 1 to 8 seconds, and of d from 1 to 6 minutes of visual angle.

Therefore after-images are similar to veiling-brightness in reducing contrasts. By reference to Fig. 22 it may be observed that the time of decay is proportional to the time of exposure and to the brightness of the light-source.

IRRADIATION

The purpose of this investigation was to determine the decrease of visual angle due to irradiation of a dark strip seen against a bright background.

The arrangement of apparatus was such that the observer was seated in front of a screen illuminated to a brightness of F. In the center of the screen was an opening, having a movable shield, behind which a diffuse light-source was placed which had a brightness of B_2. The

test-object was placed immediately in front of the diffuse light-source and at a distance of 344 cm from the eyes of the observer. Thus by withdrawing the shield the test-object was seen through the center of the opening in the screen against a background of brightness B_2. An observation consisted in adapting the eyes to the brightness F of the screen, then adjusting the brightness of the light-source to such a value B_2 that the test-object was just visible the instant the light-source was exposed by the withdrawal of the shield. Several forms of test-objects were employed, but the results were substantially the same for all of them. One of these test-objects was an opaque ring of 34 mm outside

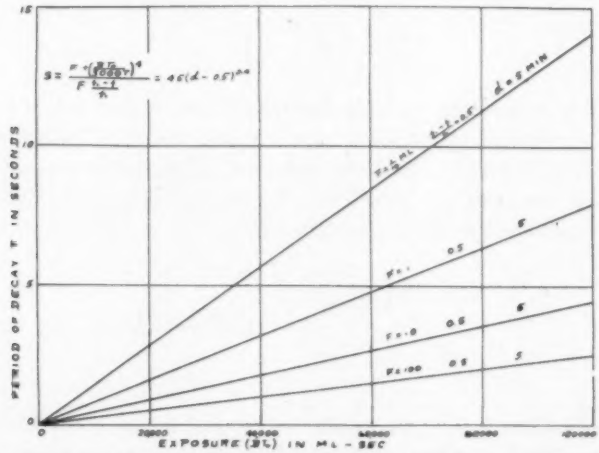

FIG. 22. *Showing the number of seconds T which must elapse after an exposure of the eyes for T_0 seconds to a light source of brightness B ml before a test-object upon the screen can be seen, the eyes having been previously adapted to the brightness of F ml. The test-object is of form shown at D in Fig. 3 and visual angle d=5 min.*

diameter, and of such an inside diameter as to give a radial width which subtended a visual angle of A minutes when seen at a distance of 344 cm. In curve A, Fig. 23, are plotted the visual angles A in minutes of the radial width of the test-object for an adapting brightness F of 1/10 ml and for various brightnesses B_2 of the light-source. Curves B, C, D, and E are for adapting brightnesses F of 1, 10, 100, and 1000 ml respectively. An empirical equation satisfying, approximately, all these curves are, visual angle

$$A = 10.7 \log B_2 - 2.07 \log F - 37.4 \text{ minutes} \qquad (20)$$

BLINDING-BRIGHTNESS

This investigation was designed to determine the brightness of a light-source which produced a distinct sense of over-exposure when viewed with an eye pre-adapted to a lower brightness.

The arrangement of apparatus consisted of a white screen containing a circular opening, behind which was placed a large gas-filled tungsten lamp in a white diffusing spherical globe and in front of which was placed a movable shield under the control of the observer. The projected area of the lamp globe seen by the observer was varied by placing over the opening in the screen various diaphragms containing circular

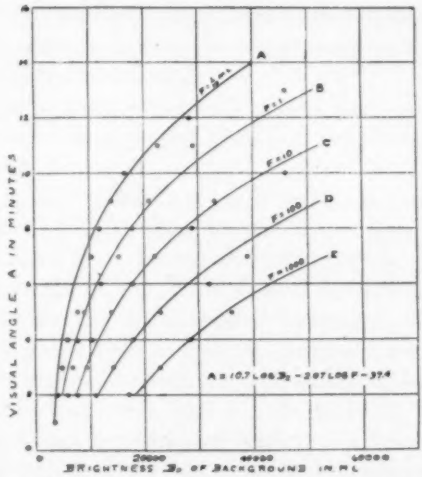

FIG. 23. *Curves showing the visual angle A in min. of an opaque test-object rendered just invisible by irradiation due to viewing it against a background of brightness B_2 ml, at five different adaptation brightnesses F of the surrounding field.*

openings concentric with the opening in the screen. The screen was placed at a distance of 244 cm from the eyes of the observer and was maintained at a uniform brightness of F.

In making an observation, the projected area of the glare-source was first adjusted by using the appropriate diaphragm and the brightness of the screen was adjusted to a value of F. Then the brightness of the glare-source was varied until the observer was satisfied that it was of a "blinding" brightness. It was found that variations of the diameter of the glare-source from 18 cm to 30.5 cm had little or no influence upon the results. Though there was no standard of judgment other than a

rather definite sensation, yet the observations of various observers were in general accord. The relation of blinding-brightness, B, in ml of the glare-source to the brightness, F, in ml of the surrounding field for values of F from 1/10 to 100 ml is represented by empirical equation

$$\log B = 3.3 + 0.3 \log F \qquad (21)$$

The average results for several observers are plotted in Fig. 24 to both arithmetic and logarithmic scales.

PSYCHO-PHYSIOLOGICAL EFFECTS OF LIGHT-SOURCES

This series of investigations was for the purpose of determining how the sensation of pleasure or discomfort in looking at a light-source is affected by its size, its brightness, or the brightness of the background

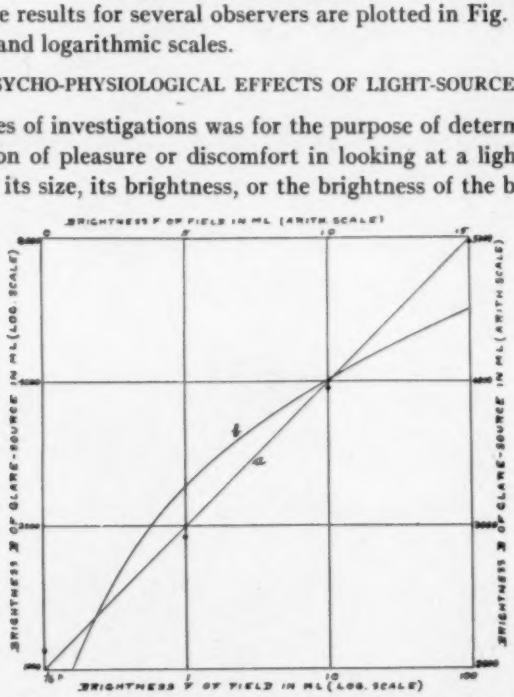
BRIGHTNESS F OF FIELD IN ML (ARITH SCALE)
BRIGHTNESS B OF GLARE-SOURCE IN ML (LOG. SCALE)
BRIGHTNESS B OF GLARE-SOURCE IN ML (ARITH SCALE)
BRIGHTNESS F OF FIELD IN ML (LOG. SCALE)
a
b

FIG. 24. *Showing the relation of brightness F of the adapting field to the brightness B of the light-source which, when looked at direct is just of a "blinding brightness."* Curve *a* is plotted to logarithmic scales and curve *b* to arithmetic scales (upper and right-hand scales).

against which it is seen. It was found much easier for the observer to appraise these sensations when the exposure of the light-source was brief rather than prolonged. Therefore, what was appraised or measured was the shock or sensation the light-source afforded when exposed but for a short time. During the investigation two methods were employed —one a comparative and the other an absolute.

When using the comparative method, the screen of brightness F was placed at distances of either 244 or 344 cm from the eyes of the observer. To one side of the center of the screen an opening was made through

which the comparison lamp was seen when the shield was withdrawn. At the other side of the center of the screen a similar opening was made through which another light-source could be observed by withdrawing its shield. By maintaining the comparison light-source fixed, and varying the size and brightness of the other, curves of equal sensations or shocks for brief exposures of the light-sources of various sizes and brightnesses were obtained.

When the absolute method was employed only a light-source of variable size and brightness was used. In making an observation, the area of the light-source was first adjusted and then its brightness for the desired effect,—for example, "maximum pleasure." Then its area was varied and its brightness again adjusted to give the same sensation for a momentary glimpse. In this way, curves of equal sensation or shock, were obtained for diverse conditions.

Results arrived at by the two methods showed fairly good agreement, especially when only the projected area and brightness of the light-source were varied.

Influence of Size and Brightness of Light-Source. In this investigation a study was made of the influence of the size and brightness of the light-source upon the pleasure or discomfort in viewing it.

The observer was placed with his eyes at a distance of 244 cm from the screen, and by the use of diaphragms containing circular openings varying from 1.75 to 30.5 cm in diameter, placed concentrically with the openings in the screen, the solid angle Q, subtended by the projected areas of the light-source, was varied from 4.15×10^{-5} to 912×10^{-5} steradians. Preparatory to making an observation, first the brightness of the screen was adjusted to F, secondly each light-source was fitted with the diaphragm containing the desired size of opening, and finally, the brightness of the comparison light-source adjusted to give a prescribed sensation or shock when momentarily exposed. In making a comparison, the brightness of the test light-source was varied until each lamp gave the same sensation when exposed. In Fig. 25 are shown the relations obtained by three observers of the brightness B of the light-source to the solid angle Q it subtended, when the adapting screen had a brightness F of 10 ml and the sensation of the shock was "perceptibly uncomfortable." It may be observed from the curve of equal sensations, that the brightness B varied inversely as the one-fourth power of the solid angle Q.

Influence of Brightness of Background. This investigation was made for the purpose of determining the influence of the brightness of the

background against which a light-source was seen upon the pleasure or discomfort experienced in viewing it.

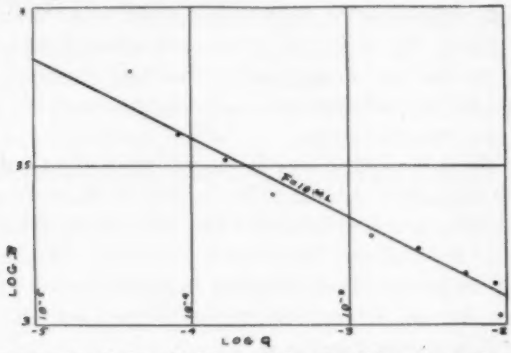

FIG. 25. *Showing the relation of brightness B in ml of light-source to the solid angle Q in steradians subtended by the projected area for "perceptibly uncomfortable" shocks of equal sensation when momentarily exposed, and when the background brightness F was 10 ml.*

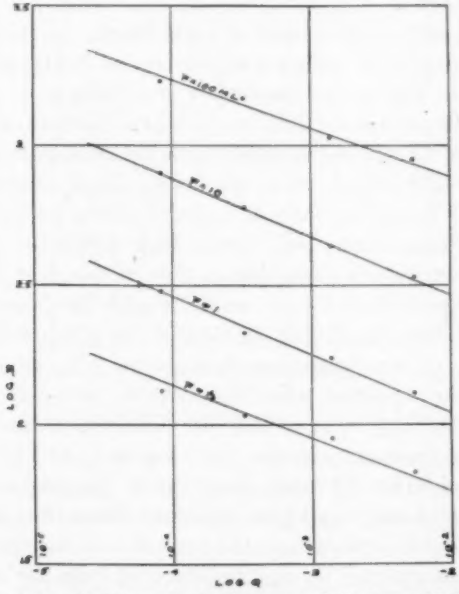

FIG. 26. *Showing relation of brightness B of light-source to its background brightness F for equal psycho-physiological sensations deemed "just not unpleasant."*

Both the comparative and absolute methods were employed in the solution of the problem. In Fig. 26 are plotted results obtained by one

observer when using the absolute method, and for adaptation or background brightnesses F of 1/10, 1, 10, and 100 ml. In making each and every reading the observer varied the brightness of the light-source to give a sensation which was "just not unpleasant" when momentarily exposed, and therefore, of equal shock. These results are illustrative of those obtained with other observers under various conditions. It appears, therefore, that for equal shocks from a given light-source, its brightness B must increase with some power of the brightness of the background. This power lies somewhere between 0.15 and 0.4 with a probable average value of 0.3

Measure of the Sensation or Shock. From an analysis of the results of all observers under various conditions, it appears that the character of sensation or shock due to a momentary exposure of the light-source may be expressed approximately by the empirical equation

$$K = \log B + 0.25 \log Q - 0.3 \log F \qquad (22)$$

where K expresses the magnitude of the shock or the psycho-physiological sensation. Average values of K are equal to

0.3 when sensation is scarcely noticeable
0.6 " " " most pleasant
0.9 " " " still pleasant
1.2 " " " at limit of pleasure
1.5 " " " very comfortable
1.7 " " " still comfortable
1.8 " " " less comfortable
1.9 " " " at boundary between comfort and discomfort
2.2 " " " perceptibly uncomfortable
2.4 " " " uncomfortable
2.6 " " " at boundary between objectionable and intolerable

2.8 (and above) when sensation is irritating (higher values painful). F is the brightness of the background in ml against which the light-source is seen, B is the brightness of the light-source in ml, and Q is the solid angle in steradians subtended by the projected area of the light-source.

VARIATIONS OF PUPILLARY APERTURE

The pupil, the gateway of visual impressions, is the circular aperture in the colored diaphragm, known as the iris. The size of this aperture is varied by two sets of muscular fibers, the first, a radial set for dilating it, and the other, a circular set for contracting it. The actions of these

muscles are controlled by reflex nerve impulses emanating from the brain.

Since the size of the pupillary aperture determines the amount of light entering the eye, the brightness and definition of the retinal image, the depth of focus, etc., it appeared desirable to know the laws of variation of the pupil so that we may plan systems of lighting that assure more efficient use, and less abuse of our eyes.

Pupillometer. The instrument used in this investigation for measuring the diameter of the pupil of the observer's eye is what might be termed a double-pin-hole pupillometer, and is shown in Fig. 27. L_4 is a light-source in a frosted bulb or behind a diffusing glass, the light from which shines through two pinholes, a_1 and a_2 formed by a horizontal slit in a

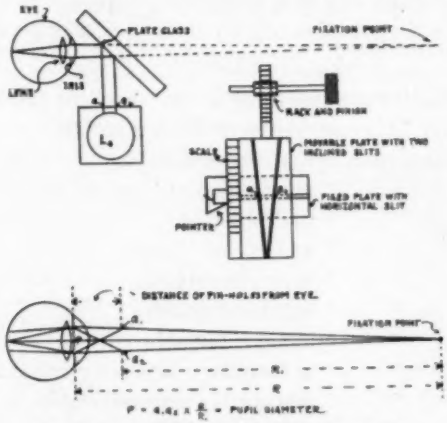

FIG. 27. *Sketch of double-pin-hole pupillometer.*

fixed plate and two inclined slits in a movable vertical plate, as shown. The light through pinholes a_1 and a_2 is reflected from a surface of a plate glass reflector into the eyes of the observer, producing two retinal images. When the eye is fixated upon a distant point and the two retinal images appear tangent, the diameter of the pupil is proportional to the distance between pinholes a_1 and a_2. As may be seen from Fig. 27, the diameter of the pupil is equal to the distance between a_1 and a_2 increased in the proportion of R/R_1. The brightness of the retinal images of pinholes a_1 and a_2 may be regulated by varying the voltage of the light-source L_4 or increasing the reflection-factor of the plate glass reflector as by quarter, half, or full silvering a very small area. The brightness of these retinal images was kept as low as possible, and

as little obstruction as possible was offered to the entry of light to the eye from the field of view. In making a measurement of the diameter of the pupil, the right eye of the observer was placed close behind the reflector of the pupillometer, and both eyes fixated upon a point distant R cm in front of the observer. Throughout this investigation, the distance R was 100 cm unless otherwise stated.

Variation of Pupils with Field Brightness. The arrangement of apparatus used for determining the diameter of the pupil for various brightnesses of the adapting field is shown in Fig. 28. The interior of the adaptation chamber was maintained at a uniform brightness of F by use of tungsten lamps L_1 and L_2. The observer viewed the interior of the adaptation chamber for ten or fifteen minutes until his eyes were thoroughly adapted to the brightness F within; then he focused his gaze upon the fixation point one meter distant and set the double-pinhole

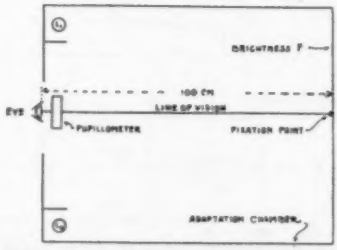

FIG. 28. *Arrangement of apparatus used in the study of variations of diameter of the pupil.*

pupillometer for a tangency of the two retinal images in his right eye. The diameter P in mm of the pupil of his right eye was then equal to the distance in mm between the pinholes multiplied by R/R_1, where $R=100$ cm and $R_1=93.5$ cm.

In Fig. 29 are shown the results obtained with three observers, in which the diameter P of the pupil in mm is plotted as ordinates and the brightness F in ml of the adapting field plotted as abscissa. Upon analysis, the empirical equations to these curves appeared of the form

$$P=K_3\epsilon^{-.16(F+C)^{0.4}} \tag{23}$$

where ϵ is the base of the natural or Naperian System of logarithms, and K_3 and C are constants. Constant K_3 is the diameter of the pupil for darkness adaptation, and constant C a residual due to inadequate adaptation or possibly a result of eye strain or the like. In Fig. 30 are plotted computed values for P for a probable average healthy

young eye, free from strain, and thoroughly adapted. The equation used was

$$P = 7\epsilon^{-.16\,F^{0.4}} \tag{24}$$

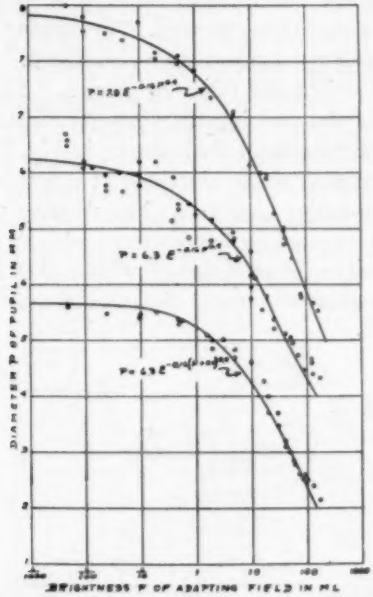

FIG. 29. *Curves showing the variation of the pupil diameter P with brightness F of the adapting field for three observers. (Note different scales for ordinates.)*

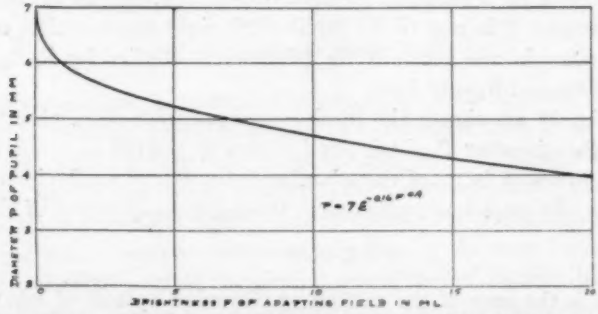

FIG. 30. *Curves showing relation of pupil diameter P to brightness F of adapting field for average eye.* Equation, $P = 7\epsilon^{-.16F^{0.4}}$ mm

Influence of Unidirectional Illumination upon Pupil Diameter. This investigation was made to determine the influence upon the pupillary

aperture of a unidirectional component of illumination at the eye when it makes an angle with the line of vision.

The arrangement of apparatus employed is shown in Fig. 31. The adaptation chamber consisted of a box about one meter long, the interior of which was maintained at a uniform brightness of F by lamps L_2 and L_3. L_1 was a dazzle-source consisting of a gas-filled tungsten lamp in a 10-inch white diffusing globe, placed two meters from the observer's eye and at an angle of D degree above his line of vision. The brightness of the globe was B, and its area projected to the view of the observer was varied by interposing various disks, each with a circular opening which subtended a solid angle of Q steradians from the observer's eyes. Therefore the unidirectional illumination E at the observer's eyes was 10 BQ/π meter-candles. A movable shield under the control of the observer was used for exposing or shielding the

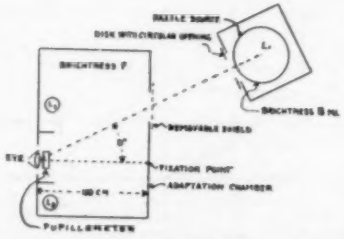

FIG. 31. *Arrangement of apparatus used in investigating the effect upon the diameter of the pupil of flashes of unidirectional illumination.*

eyes from the light-source. A determination consisted in measuring the diameter of the pupil of an observer under two conditions. First, a measurement was made of the diameter, P_0 of the pupil with the eyes fixated on a point a meter distant and thoroughly adapted to the uniform brightness F of the interior of the adaptation chamber. Next, the eyes were fixated upon the point a meter distant, the shield was withdrawn, exposing the eyes to the unidirectional component of illumination E, from the dazzle-source located D degrees above the fixation point, and when the eyes had become thoroughly accustomed to the combination of lighting, the pupil diameter P' was measured by adjusting the pupillometer to give a tangency of the retinal images of the two pinholes of the pupillometer. Thus P_0 was the diameter of pupil in mm corresponding to a uniform brightness of field of F; and P' was the diameter of pupil in mm corresponding to the field brightness

of F, augmented by E meter-candles of unidirectional illumination at the eye from the dazzle-source.

Owing to the added component of unidirectional illumination of E the pupil contracted from P_0 to P', corresponding to a field brightness greater than F. Having previously determined for the observer the diameter of the pupil corresponding to various field brightnesses as shown in Fig. 29, we determined to what field brightness the pupil diameter P' corresponded. In this way, the brightness increase in ml per meter-candle of unidirectional illumination at the observer's eyes was determined for three observers for various angles D of the dazzle-source above their line of vision. The average results for the three

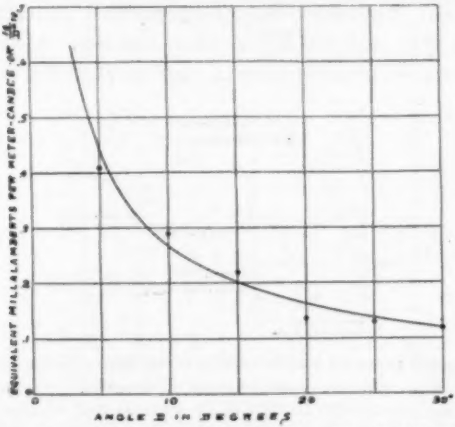

FIG. 32. *Showing the number of milliamberts of uniform illumination having an equal effect upon the diameter of the pupil as one meter-candle at the eye from a dazzle-source located D degrees above the line of vision.*

observers are plotted in Fig. 32, and are fairly well satisfied by the empirical equation

$$\text{equivalent millilamberts increase per meter-candle} = \frac{1.85}{(1.122)^D} \quad (25)$$

It is therefore evident that, as the angle D between dazzle-source and line of vision increased, the effect upon the pupil of a meter-candle of illumination at the eye steadily decreased, so that its effect at 25 degrees was only about 1/10 its effect at 5 degrees. By substituting this result in Eq. (24) an empirical formula has been obtained by which the average diameter of pupil can be calculated for any condition of illumination; it is

$$P = 7\epsilon^{-.16\left(F+\frac{1.85}{(1.122)^D}E\right)^{.4}} \quad (26)$$

In order to illustrate the effect upon the diameter of the pupil, of a given intensity of unidirectional illumination, there have been plotted in Fig. 33 computed values for P for the average eye for general brightness F of 1/10, 1, and 10 ml, respectively, when E meter-candles of illumination from a dazzle-source elevated 10 degrees above the line of vision shine into the eyes.

Effect of Sudden Increases of Field Brightness. Having investigated the influence of long-time exposures upon the pupil diameter, a study was next made of the effect of momentary increases in the brightness of the field.

The arrangement of apparatus used is shown in Fig. 28, with the exception that means were provided for producing minute, moderate or large sudden increases of the brightness of the interior of the adapting

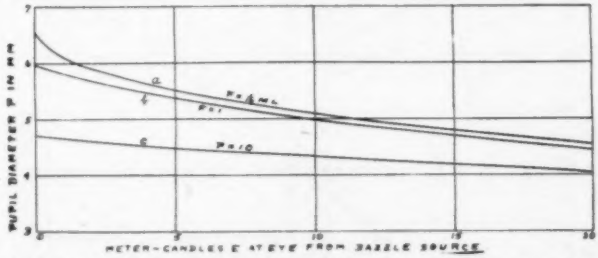

FIG. 33. *Curves showing the diameter of pupil of the average eye accommodated for one meter when exposed to a uniform field of F ml and E meter-candles from a dazzle-source elevated 10 degrees above the line of vision: a* is for $F = 1/10$ ml; *b*, for $F = 1$ ml; and *c*, for $F = 10$ ml.

chamber. This increase of brightness was usually obtained by momentarily short-circuiting a resistance in series with lamps L_1 and L_2, or lighting one or more additional lamps. A determination consisted in making two observations of the pupil diameter: the first observation was of the pupil diameter P_0 at the field brightness of F_0; the next observation was of the pupil diameter P' after it had contracted due to the increase of field brightness from F_0 to $F.'$ A plot of the results obtained with three observers is shown in Fig. 34. These results are fairly well satisfied by the empirical equation

$$\frac{P_0 - P'}{P_0} = 0.21 + 0.025 \log F_0 + 0.205 \log\left(\frac{F' - F_0}{F_0}\right) \qquad (27)$$

In order to show the relative contraction of the pupil due to momentary relative increase of field brightnesses, curves are plotted in Fig. 35 for initial or adapting field brightnesses F of 1/100, 1/10, 1, 10, and 100 ml.

In order that there shall be no contraction of pupil with momentary increases of field brightness, our formula requires that the proportional increase of field brightness

$$\frac{F'-F_0}{F_0} < \frac{0.095}{F_0^{.122}} \tag{28}$$

which is less than about 5% for $F=100$ ml, and less than 17% for $F=0.01$ ml, as may be seen from Fig. 35.

Effect of Momentary Flash of Dazzle-Source. This investigation was designed to determine the contraction of the pupil due to a flash of unidirectional illumination from a dazzle-source.

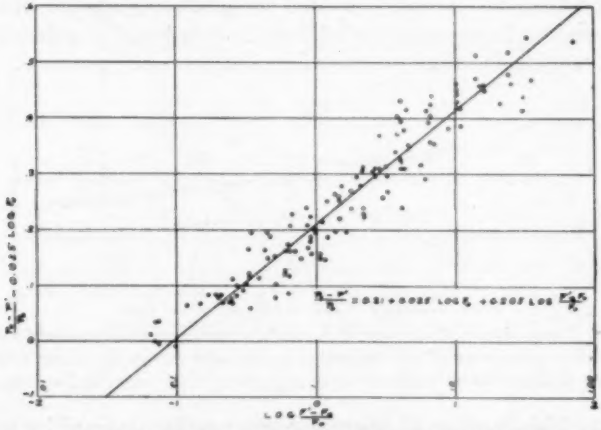

FIG. 34. *Showing the relationship between relative contractions of pupil diameter and momentary increases of the general field brightness from F_0 to F' ml.*

The arrangement of apparatus used is shown in Fig. 31. The dazzle-source was a gas-filled tungsten lamp in a white spherical diffusing globe, situated at an angle of D degrees above the line of vision, and having a brightness of B. A determination consisted in making measurements of the pupil diameter under two conditions. First, the eyes were thoroughly adapted to the brightness F_0 of the interior of the box, then the eyes were focused upon the fixation point and the diameter P_0 of the pupil measured. For the second determination, the eyes are again focused upon the fixation point, then the shield withdrawn momentarily exposing the eyes to a unidirectional component of illumination of E mc from the dazzle-source located D degrees above the line of vision and the diameter P' measured of the contracted pupil.

Determinations were made on the same three observers as used in the foregoing, with the angle D varied from 5 to 30 degrees, with B varied from 100 to 4000 ml and with F_0 varied from 0.005 to 20 ml. The results obtained with D equal to 5, 10, and 15 degrees are plotted in Fig. 36. From an analysis of the results it appears that they are fairly well satisfied by the empirical equation

$$\frac{P'}{P_0} = 0.79 - 0.025 \log F_0 - 0.205 \log \left(\frac{1.4\,E}{F_0 D^{0.72}} \right) \tag{29}$$

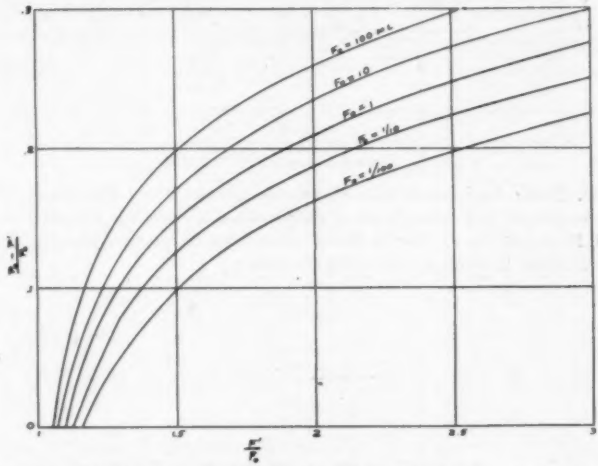

FIG. 35. *Curves showing the ratio of change of pupil diameter due to an increase of brightness of the general field from F_0 to F' ml when the adapting brightness F_0 is 1/100, 1/10, 1, 10, and 100 ml respectively.*

By subtracting either side of the above equation from unity it becomes

$$\frac{P_0 - P'}{P_0} = 0.21 + 0.025 \log F_0 + 0.205 \log \left(\frac{1.4\,E}{F_0 D^{0.72}} \right)$$

$$= 0.21 - 0.18 \log F_0 + 0.205 \log \left(\frac{1.4\,E}{D^{0.72}} \right) \tag{30}$$

By comparing Eq. (30) with Eq. (27) it may be seen that the flash of one meter-candle of unidirectional illumination upon the eye from a dazzle-source D degrees above the line of vision was approximately equal to $1.4/D^{0.72}$ ml increase of general field brightness, as shown in Fig. 37.

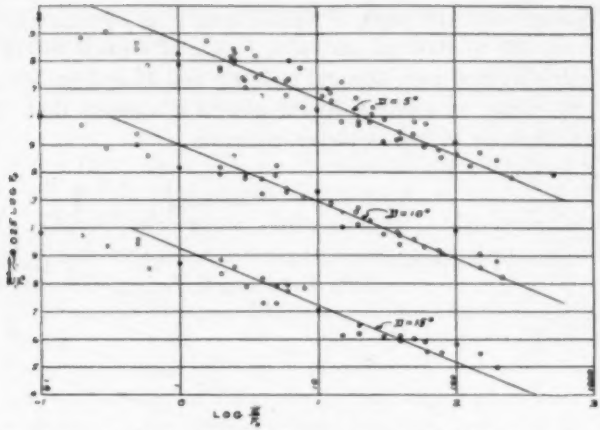

FIG. 36. *Curves showing the relation of contracted diameter P′ to initial diameter P_0 of pupil of three observers for momentary flashes of unidirectional illumination E from a dazzle-source elevated 5, 10, and 15 degrees above the line of vision, when the eyes were pre-adapted to uniform brightness of F_0 ml. (Note the different scales of ordinates.)*

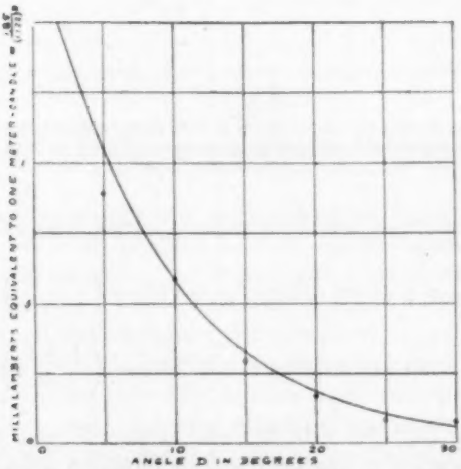

FIG. 37. *Showing the number of millilamberts momentary increase of uniform brightness of field having an equal effect in contracting the pupil as one meter-candle of unidirectional illumination at the eye from a dazzle-source located D degrees above the line of vision.*

Variation of Pupil Diameter with Accommodation and Convergence. Previously, attention has been called to the fact that the eyes were focused upon a point a meter distant. At about this distance the diameter of the pupils of the observers' eyes were approximately a maximum for the given field brightness. This may be seen by reference to Fig. 38 in which pupil diameter P is plotted against the distance R for which the eyes were accommodated. In this test the light-source was a diffusing disk of 5 cm diameter placed at 30 cm from the eyes and 13 degrees to the left of the line of vision, and gave 67 meter-candles at the eye. The data is the average for two observers.

In order to differentiate between the effects of change of focal length of the lenses of the eyes and the convergence of the eyes, an investiga-

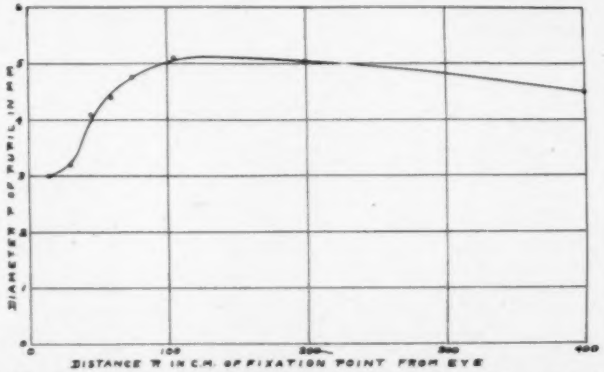

FIG. 38. *Showing the variation of the pupil diameter with distance R of the eye from the fixation point.*

tion was made when the focal accommodation was held constant and the convergence varied. This was accomplished by maintaining a constant adapting brightness and stationary fixation point but inserting in the line of vision of each eye, a prism with its base projecting outwards. In the test the brightness of the adapting field was maintained at 2 ml, the vision was fixed upon a point one meter distant, and measurements of the pupil made for additional convergences of 0, 7.5, and 15 degrees. These data are plotted in curve *a*, Fig. 39. For comparison, the data in Fig. 38 has been replotted in curve *b*, Fig. 39, from which it is evident that much of the change of pupil diameter in accommodation is due to change of convergence of the eyes.

Influence of Pupil Diameter upon Vision. When there are severe fluctuations in illumination, the eyelids involuntarily close for the ex-

clusion of light and thus supplement the action of the pupils; but assuming no interference from the lids, the pupillary area determines the amount of light that enters the eye. Under normal conditions it is evident that the brightness of a retinal image is proportional to the area of the pupil or to the square of the pupil diameter. This applies to the peripheral as well as central retinal images.

When the pupil is contracted the axial or central portion of the lens is employed. The peripheral zones of the lens of the eye are the portions which produce most of the aberrations or errors of refraction. Therefore it is apparent that with contracted pupils the definition of the retinal image is improved, which is of special interest in seeing fine

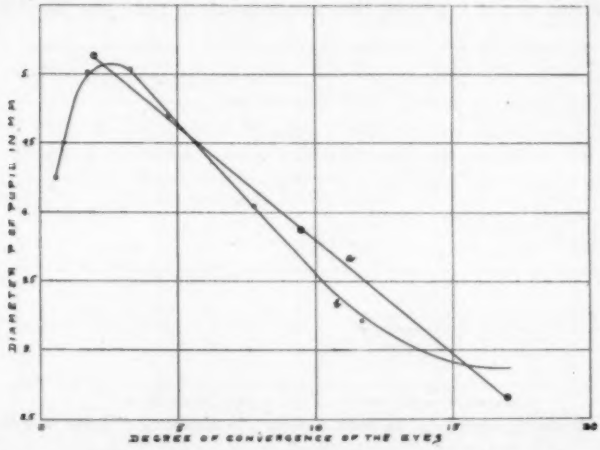

FIG. 39. *Showing variation of the pupil diameter with degrees of convergence: a,* without change of the lens adjustment; *b,* with normal change of lens adjustment.

detail. From Figs. 38 and 39 it may be observed that this adjustment of pupils is automatic for near vision.

Contraction of the pupils also results in an increase of depth of focus. On the other hand, a contraction of the pupil tends to decreases the resolving power of the eye or to decrease its visual acuity.

Influence upon Pupil of Size and Brightness of Field. This investigation was for the purpose of determining the variation of the pupil diameter with the size and brightness of a light-source viewed direct.

The apparatus consisted of a screen with a hole in its center through which a gas-filled tungsten lamp in a 12-inch white diffusing globe was seen. The projected area of the lamp was varied by interposing disks containing circular openings varying in diameter from 5 to 22 cm. The

disks were placed about 117 cm from the eyes of the observer, therefore the solid angle Q subtended by the projected area of the light-source was varied from 14.2×10^{-4} to 270×10^{-4} steradians. The brightness B of the light-source was varied from 32 to 5700 ml. A determination consisted in the observer viewing the light-source steadily for several minutes and then measuring the diameter of his pupil. The average

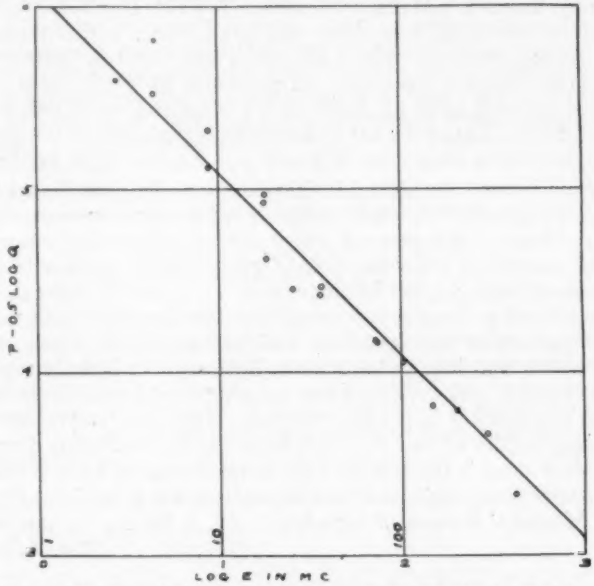

FIG. 40. *Showing the variation of pupil diameter with the illumination E at the eye from a light-source of uniform brightness B when viewed direct and whose projected area subtended a solid angle of Q steradians.*

results of two observers are plotted in Fig. 40, which are approximately satisfied by the empirical equation

$$P = 6.1 + 0.5 \log Q - \log E$$

or

$$= 5.6 - 0.5 \log Q - \log B$$

where E was varied from 1 to 420 mc. The brightness of the screen was very low but unfortunately not measured.

This investigation[1,2] was carried out in the Lighting Research Laboratory of the National Lamp Works of the General Electric Co., Nela Park, Cleveland, Ohio, and thanks are hereby expressed to M. Luckiesh, Director of the Laboratory, for suggesting the investigation, and for other helpful suggestions.

[1] Luckiesh and Holladay, Tr. I. E. S., *20*, p. 221; 1925.

[2] Luckiesh, Taylor and Holladay, J.O.S.A. & R.S.I., *11*, p. 311, Oct., 1925.

Analysis of the Spectrum of Once-ionized Vanadium.—This analysis is based on mappings of the spark-spectrum of V from 2050 to 6500A by the author (in which spark lines are discriminated from arc lines by arranging the exposure so that the known arc lines appear in about the same intensity as in comparison arc-spectra, and selecting the lines which appear definitely brighter than in the comparison spectrum), with assistance from an earlier mapping and from Zeeman-effect studies by Babcock. Meggers identifies S, P, P, D, F, and G terms of both triplet and quintet systems, and in addition F, G, H terms of the triplet system; they conform to Laporte's selection-rule (that combinations occur beween overlined terms when $\Delta k = \pm 1$, between not-overlined terms if $\Delta k = \pm 1$, between an overlined and a not-overlined term if $\Delta k = 0$). This does not exhaust the complexity of the spectrum, as there are extra sequences of terms which have to be distinguished by prefixed letters; for instance, there are a^5F, b^5F and $\overline{F}$ sequences of terms to all of which the same values 4 for k and 5 for r are attached. The occurrence of H terms for which $k=6$ is of peculiar interest, and so is the absence of D terms. The Zeeman effects agree with Landé's rules in most instances, but for some there are certainly slight deviations in the values of g. Singlet terms could not be identified with certainty. The comparison of this spectrum with the spectrum of the preceding neutral atom, titanium, is important. Both spectra include triplet and quintet systems, and overlined and not-overlined terms; from both the D terms are missing, a peculiar feature. There are resemblances and also dissimilarities in the intervals between corresponding terms; correlated with these is the fact that the normal state of ionized vanadium is a quintet F state while that of neutral titanium is a triplet F state.—[W. F. Meggers, Bureau of Standards; ZS. f. Phys., *33*, pp. 509-528; 1925.]

KARL K. DARROW

Atom-lattice of certain glasses and certain modifications of SiO_2.—So-called "good" glasses—inferentially mixtures of Na_2O and SiO_2 in varying proportions—when pulverized and examined by the Debye-Scherrer method, showed no evidence of crystal structure; had they contained crystal units no larger than groups of 8 atoms at the corners of an elementary cube these would have made themselves evident, according to calculation; therefore the glasses are devoid even of such rudimentary crystal structure. The anomalies exhibited by glasses near one of the critical temperatures of transformation of quartz (575°C) are therefore to be ascribed not to the presence of crystals of quartz in the glass, but possibly to some kind of alteration within the SiO_2 molecule which occurs near that temperature, whatever the environment of the molecule is. The atom-lattices of β-quartz, α-cristobalite and β-cristobalite were also determined; the first is hexagonal, the last cubic.—[N. Seljakow et al., St. Petersburg; ZS. f. phys., *33*, pp. 53-63; 1925.]

KARL K. DARROW

ON THE RELATION BETWEEN TIME AND INTENSITY IN PHOTOGRAPHIC EXPOSURE*

Third Paper

By Loyd A. Jones, Emery Huse, and Vincent C. Hall

ABSTRACT

Work has been continued on the failure of the photographic reciprocity law, $E=It$. The failure of this law using Panchromatic and Orthochromatic emulsions is somewhat greater than reported previously for high speed non-color sensitive emulsions. Slow Ordinary and Lantern emulsions show very great failure and also a marked change of gamma with intensity. In general, for fast plates the variation of density with intensity is small, optimal intensity is at a low value, and gamma is independent of intensity. For slow plates the density variation is great, optimal intensity high, and gamma drops at low intensities. As found by Kron, optimal intensity shifts to higher values with increasing development time.

Kron's usually accepted empirical law does not fit the observed data. An alternative form

$$It=\frac{I_0t_0}{2}\left[\left(\frac{I}{I_0}\right)^{a}+\left(\frac{I}{I_0}\right)^{-a}\right]$$

has been found to fit the observed data for fast plates over a range of 1:8,000,000 in intensity and to fit the data for slow plates at high intensities. For these emulsions the observed failure is greater than the calculated curve indicates at low intensities. This equation was suggested by Kron but it did not fit his observations. The observed data thus far indicate that the dependence of gamma on intensity follows as a result of changes in the effective grain size frequency function caused by a differential failure of the reciprocity law for grains of different sizes and sensitivities.

The present paper is a continuation of an investigation of the so-called photographic reciprocity law, usually expressed as

$$E=I\cdot t$$

where E is the insolation, I the intensity of light, and t the time of exposure. In two previous papers on this subject[1] it was shown that for certain photographic materials the failure of the above law was less than in general had been recorded by other observers, using other emulsions than were used in this work. Only Motion Picture Positive film showed a considerable failure, and accompanying it was a difference in the shape of the characteristic curve of the emulsion when exposures were made at different intensities. An empirical expression

$$D=K-a\sqrt{(\log I-\log I_0)^2+1} \qquad (1)$$

was applied to some of the data and was found to fit fairly well in cases where the density-log intensity curves were symmetrical with respect

*Communication No. 253 from the Research Laboratory of the Eastman Kodak Company.

[1] L. A. Jones and E. Huse, J.O.S.A. & R.S.I., *17*, p. 1079; 1923; and *11*, p. 319; 1925.

to log I_0, the "optimal" intensity of the emulsion. This expression is similar to Kron's empirical law[2]

$$E = It \cdot 10^{-a\sqrt{(\log I - \log I_0)^2+1}} \tag{2}$$

expressed logarithmically,

$$\log It = \log E + a\sqrt{(\log I - \log I_0)^2+1} \tag{3}$$

which represents a hyperbola when log It is plotted against log intensity. These curves are the "curves of constant blackening" of Kron, and of Schwarzschild, and the "isoactinics" of Halm. The curves plotted according to (1) show the variation of density with intensity for a constant amount of energy, while the isoactinics show the variation in energy for a constant density at any intensity of light. In the cases where (1) fits the observed data (2) leads very closely to the same agreement. It can be shown,[3] that in cases where the shape of the characteristic curves obtained at different intensities (the individual curves being on a time-scale of exposures) are different, the constant of (3) will be different for each curve (as for densities of 0.5, 1.0, 1.5, etc.), while if the curves are parallel the only change will be in the value of log E in (3). Optimal intensity with (1) represents the maximum amount of silver which can be made reducible with a given energy, while with (3) it represents the minimum energy required to make reducible a given mass of silver.

APPARATUS

The instrument for making exposures over the required enormous range of times and intensities has been described previously.[4] Essentially this is a time-scale sensitometer of the sector wheel type, exposures being made with one revolution of the wheel to eliminate intermittent exposures. The driving mechanism has been changed to an autosynchronous motor which stays in perfect step with the alternating current supply unless heavily overloaded. The frequency of the supply is 60 cycles per second with a maximum variation of ± 0.5 cycles per second, and under normal conditions, constant within ± 0.2 cycles per second. Thus the error is never so much as 1% in driving the sector wheel and usually can be relied on to within 1/2 of 1%. This has been found more satisfactory than the constant speed governed motor,

[2] E. Kron, Publ. Astrophys. Obs. zu Potsdam, N. 67, 1913.
[3] Halm, J. Mon. Not. R. A. S., 75, 1915, p. 159.
[4] Jones, L. A. J.O.S.A. & R.S.I., 7, p. 305; 1923.

which required frequent attention and adjustment to keep within 1% of the required speed.

Slight changes in the gearing mechanism increase the available time range from 1:500,000 to 1:4,000,000, or 3 power of two steps. The increased time range is very useful at the ends of the intensity scale, enabling correct exposures to be made over a wider range.

The light sources have been changed from concentrated filament incandescent lamps to monoplane filament lamps, using 100 watt and 250 watt lamps behind 3 sheets of diffusing glass for low intensities, and 500 watt and 900 watt (motion picture) types for the high intensities. The low intensity lamps were both color matched and photometered in their exact position in the lamp house, while the color matching of the high intensity lamps was done outside the lamp house, the intensity measurements being made in position. All exposures, unless otherwise stated, were made with the lamps running at 2500°K as compared with standards from the National Electric Lamp Association. The highest illumination used was 1280 meter candles, and the lowest .000076 meter candles. The former is about one fortieth the value of direct sunlight, while the latter is the illumination on a photographic plate when a 16th magnitude star is photographed with a 20-inch telescope, using focal images.

In order to measure the illumination on the plate at any time, a two and one-half meter photometer bench, with a Lummer-Brodhun cube comparator, was built directly on the sensitometer with one target placed exactly in the plane occupied by the plate during exposure. The bench was calibrated by placing in the sensitometer housing, at various distances, a standard lamp from the Electrical Testing Laboratories. The comparison bench was thus calibrated in terms of meter candles incident on the exposure plane, and the intensity of the various sources expressed on this basis. These changes reduce the probable error of time and intensity in exposure to about 1%. Variation of sensitivity of the emulsion over the surface of the plate, development errors, and the errors coming in photometric density measurements must be reduced considerably before any further refinement in exposure becomes necessary.

The pyro developer, as published in the second paper on this subject, was used for all materials. Normally plates were developed for five minutes at 68°F. Unless otherwise stated, the data were obtained under these development conditions.

All exposures were made on $\frac{1}{2}\times 5$ inch strips, five strips each from a different plate being exposed at each intensity. A light frame of monel metal was made so as to hold 40 of these strips in such a way that they could be developed simultaneously. Variations due to development were considerably reduced by this means.

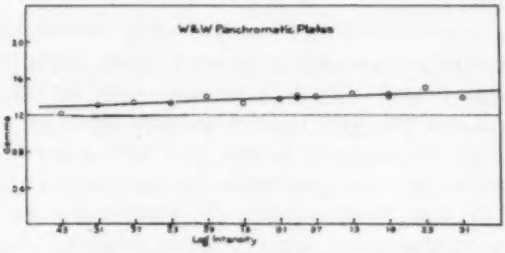

FIG. 1. *Variation of gamma with intensity (normal development).*

PHOTOGRAPHIC MATERIALS

Two color sensitive materials have been studied, Wratten and Wainwright Panchromatic, and Eastman Double Coated Orthochromatic plates; also two very slow non-color sensitive materials, Slow Ordinary (Wratten) and Eastman Slow Lantern plates.

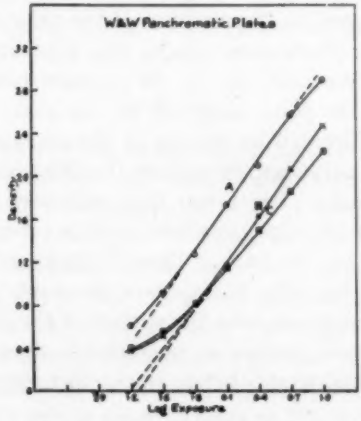

FIG. 2. *Characteristic curves for different intensities.*
A—1.25 mc, *B*—1280 mc, *C*—.00031 mc.

EXPERIMENTAL RESULTS

The data shown in Figs. 1, 2, and 3 give the results for the panchromatic plates. Fig. 1 shows the variation of gamma with intensity. For

the standard development used there is a rise of 0.16 in gamma, the slope of the straight line portion of the characteristic curve, for a range of intensity of one to eight million. Although this variation is not large, it is very definite, as will be seen when the development is carried to longer times. Fig. 2 shows the characteristic curves obtained at three different intensities, each point being the average density from five independent strips exposed on a time scale. These curves are all drawn on the same log exposure axis to show the actual differences in the curves obtained. Since the shape of the curves is slightly different no smoothing was done. Fig. 3 gives the density-log intensity curves plotted from the original characteristic curve of each intensity. The

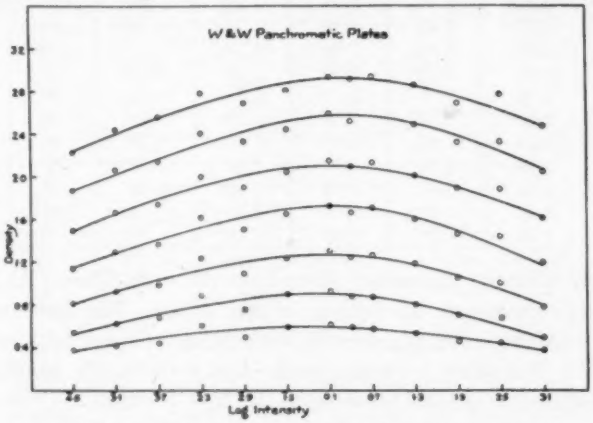

FIG. 3. *Variation of density with intensity (each curve for constant I·t).*

curves are nearly symmetrical with regard to optimal intensity, which, under the given conditions is at 0.625 meter candles for an exposure of 0.156 meter candle seconds, and shifts to 2.5 meter candles at an exposure of 10 mcs.The departure from the reciprocity law is greater than for the fast non-color sensitive materials tested previously. Table 1 contains densities read from these curves for the exposure values used. From these values, final characteristic curves have been drawn, and the log exposure for a constant density found at different intensities. When these are plotted we can apply Kron's law to the data, as will be done later (Fig. 16).

ORTHOCHROMATIC PLATES

The orthochromatic plates are somewhat faster than the panchromatic and approach more closely the behavior of the high speed

ordinary type. As can be seen from Fig. 4, there is no change in gamma over the enormous range of intensities used. Although accidental variations occur there is no systematic tendency toward a change in gamma as the intensity increases. Fig. 5 shows characteristic curves obtained

TABLE 1. *W. & W. Panchromatic Plates*

DENSITY

Log I	$I \cdot t$						
	10	5	2.5	1.25	.625	.312	.156
3.1	2.48	2.08	1.63	1.17	.80	.50	.39
2.5	2.62	2.25	1.78	1.34	.95	.62	.44
1.9	2.77	2.40	1.90	1.50	1.07	.71	.49
1.3	2.85	2.50	2.00	1.62	1.17	.80	.53
0.7	2.91	2.57	2.08	1.70	1.24	.87	.57
0.1	2.91	2.58	2.11	1.73	1.27	.91	.60
1.5	2.86	2.52	2.08	1.69	1.25	.90	.60
2.9	2.79	2.43	2.01	1.62	1.20	.86	.59
2.3	2.68	2.31	1.92	1.52	1.13	.79	.54
3.7	2.55	2.17	1.79	1.40	1.03	.71	.49
3.1	2.40	2.02	1.65	1.27	.92	.62	.43
4.5	2.24	1.86	1.49	1.14	.81	.54	.37

at widely different intensities plotted on the same scale. As before, each curve represents an average of five strips. The low and high intensity curves practically coincide with the optimal intensity exposure at the left, indicating a higher speed. Fig. 6 shows the density-log I curves plotted from data taken from the H & D curves. These curves

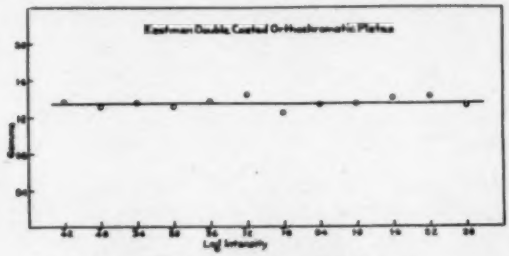

FIG. 4. *Variation of gamma with intensity.*

are quite similar to the ones for panchromatic plates, but the optimal intensity is lower. There is no appreciable change in optimal intensity with increasing exposure as was the case with the panchromatic plates, and also the falling off in efficiency at the high intensity end is apparently not quite so rapid.

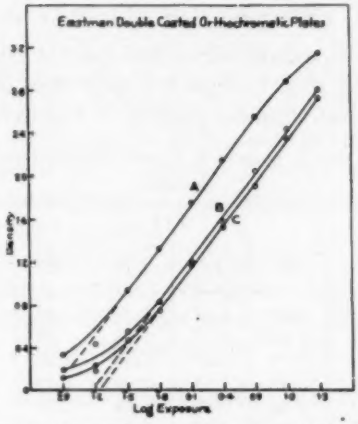

FIG. 5. *Characteristic curves for different intensities.*
A—.16 mc, *B*—640 mc, *C*—.00016 mc.

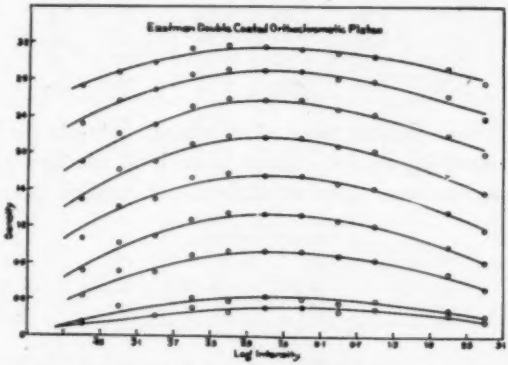

FIG. 6. *Density-log intensity curves.* (*Each for a constant I·t*).

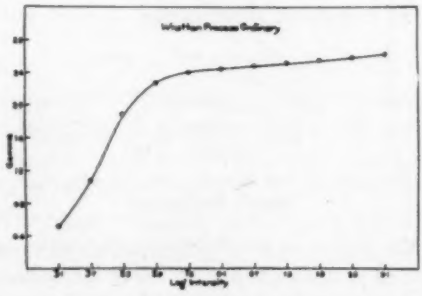

FIG. 7. *Variation of gamma with intensity.*

WRATTEN SLOW ORDINARY

For this process type emulsion we find that the failure is far greater. As can be seen from Fig. 7, there is a large drop in gamma as lower intensities are reached. Gamma drops from 2.62 to 0.50 in an intensity

TABLE 2. *Eastman D. C. Orthochromatic Plates*

DENSITY

log I	$I \cdot t$								
	20	10	5	2.5	1.25	.625	.3125	.156	.039
2.8	2.81	2.45	2.05	1.57	1.19	.82	.54	.23	.18
2.2	2.90	2.57	2.18	1.73	1.35	.97	.65	.29	.22
1.6	2.98	2.67	2.29	1.87	1.48	1.10	.75	.34	.26
1.0	3.05	2.76	2.39	1.99	1.60	1.20	.83	.38	.30
0.4	3.09	2.82	2.48	2.08	1.68	1.27	.88	.41	.32
1.8	3.13	2.87	2.54	2.14	1.73	1.32	.92	.43	.32
1.2	3.15	2.89	2.56	2.16	1.75	1.32	.93	.43	.31
2.6	3.13	2.87	2.54	2.13	1.73	1.30	.90	.41	.29
2.0	3.08	2.79	2.46	2.05	1.63	1.22	.84	.38	.26
3.4	2.99	2.68	2.31	1.92	1.54	1.10	.74	.32	.22
4.8	2.87	2.54	2.13	1.75	1.36	.95	.61	.25	.18
4.2	2.73	2.36	1.91	1.52	1.17	.74	.46	.17	.12

range of one to one million, most of the change being in the lower one-third of the intensity range. There is no limit reached at the high intensity end, however, since at 1280 meter candles gamma is still

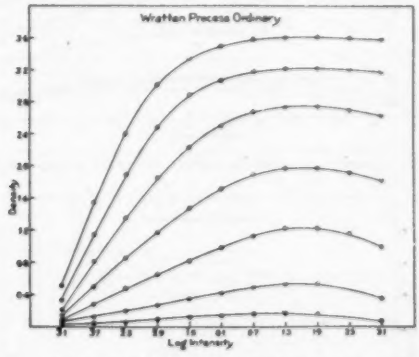

FIG. 8 *Variation of density with intensity. Each curve for a constant $I \cdot t$ value (normal development).*

increasing. In the region of low intensity the curve apparently tends toward a less rapid gamma change at lower intensities. Fig. 8 shows the density-log I curves, the top curve being for an exposure of 160 mcs

each succeeding curve decreasing by a factor of 1/2. Optimal intensity for the highest exposure is 160 meter candles, and for the lowest about 10 meter candles. If we assume that density is proportional to the mass of silver throughout the entire range, the lowest illumination is only 14% as efficient as the highest for an exposure of 160 mcs. Thus it is important, when considering the amount of energy necessary to render silver halide grains developable, to consider the *rate* of energy flow as well as the total incident amount.

The low exposure curves show a "flattening" at extremely low intensities, approaching a constant low density. This point has been observed by H. J. Channon,[5] but has never been directly connected to the behavior of the plate at high intensities. Table 3 gives the density

TABLE 3. *Wratten Slow Ordinary Plates*

DENSITY

log I	$I \cdot t$						
	160	80	40	20	10	5	2.5
3.1	3.58	3.18	2.63	1.82	1.00	.36	.07
2.5	3.60	3.21	2.69	1.91	1.16	.46	.12
1.9	3.61	3.22	3.74	1.97	1.22	.53	.16
1.3	3.60	3.21	2.74	1.97	1.22	.52	.16
0.7	3.58	3.18	2.68	1.89	1.12	.48	.16
0.1	3.49	3.07	2.49	1.71	.98	.41	.13
1.5	3.34	2.88	2.23	1.47	.81	.34	.11
2.9	3.01	2.48	1.85	1.17	.64	.26	.09
2.3	2.40	1.89	1.36	.85	.47	.19	.07
3.7	1.54	1.15	.81	.49	.27	.12	.04
3.1	0.51	.33	.21	.14	.08	.05	.02

values read from the curves of Fig. 8. Characteristic curves for different intensities are shown in Fig. 9, showing the great difference in shape when exposures are made at high and low intensities.

SLOW LANTERN PLATES

The slow lantern emulsion is similar to the previous one, being very slow and giving a high value of gamma, but it has somewhat finer grains than the slow ordinary. Its failure is also quite similar to the Process plate, as can be seen from Fig. 10 which shows the variation of gamma with intensity. The range extends to somewhat lower values of illumination than before, but no flattening of the curve is perceptible. The

[5] Channon, H. J. Studies in Phot. Science, Phot. J., *60*, p. 166; 1920.

present curve, when extrapolated to intensities of 1/4 the last observed point cuts the axis of zero gamma. It is probable, however, that experi-

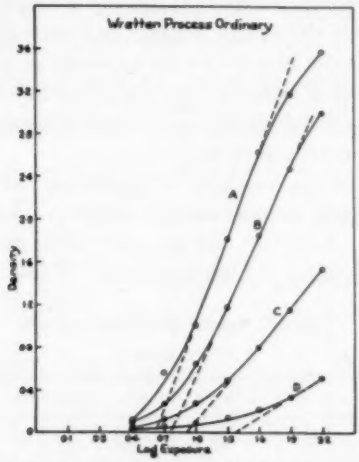

FIG. 9. *Characteristic curves for different intensities.*
A—1280 mc, *B*—.080 mc, *C*—.0070 mc, *D*—.00125 mc.

mentally the curve will flatten before reaching zero. At the high intensity end gamma reaches a maximum of 3.44 at about 640 meter candles. Fig. 11 gives the density log I curves. These show the same

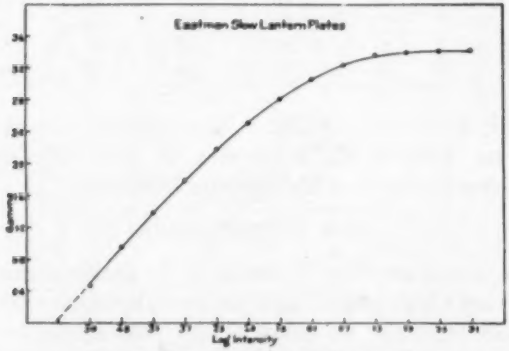

FIG. 10. *Variation of gamma with intensity.*

large drop as the gamma-log I curve, but all except the two highest exposure curves (80 and 160 meter candle seconds) show the approach to the constant low density region. At the high intensity end, the

optimal intensity for the lowest exposure curve is about 40 meter candles, but shifts to higher values so that for the 160 mcs curve it is above 1280 mc. While the exposure range used covers practical photographic work from the photography of faint stars to spark photography of rifle bullets, even greater ranges must be used to get a complete picture of the sensitivity of the silver halide grains. The characteristic curves given in Fig. 12 show the great difference obtained at different illuminations. The lowest curve required exposures (maximum) of about 26 days, while the steepest curve had a maximum exposure of

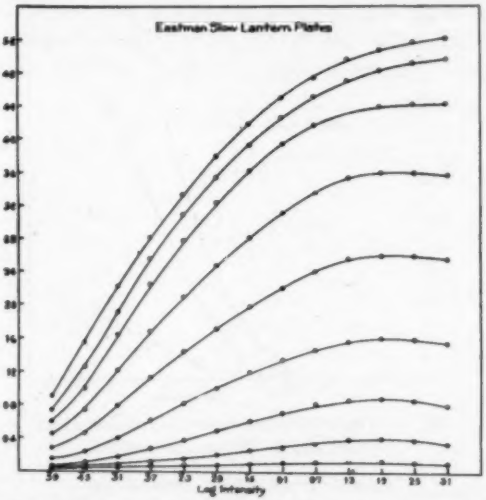

FIG. 11. *Variation of density with intensity.* (*Each curve for a constant value of I·t*).

one second. They are plotted on the same log E scale, each curve being the average of five strips. If the high densities can ever be made developable at the low intensities the exposures must be tremendously long.

The final reduced data are shown in Table 4, being read from the curves of Fig. 11. Characteristic curves drawn from these values have been used to obtain the curves of constant density shown in Fig. 19.

THE EFFECT OF DEVELOPMENT

The importance of control of the extent of development for work on the failure of the reciprocity law was first noticed by Kron (loc. cit.) who showed that optimal intensity shifts to higher values as the time of development increases. He did not attempt any explanation of this

phenomena, nor did Halm (loc. cit., p. 165), who refers to Kron's data and concludes that the amount of failure is constant at all development times but that the optimal intensity shifts as found by Kron.

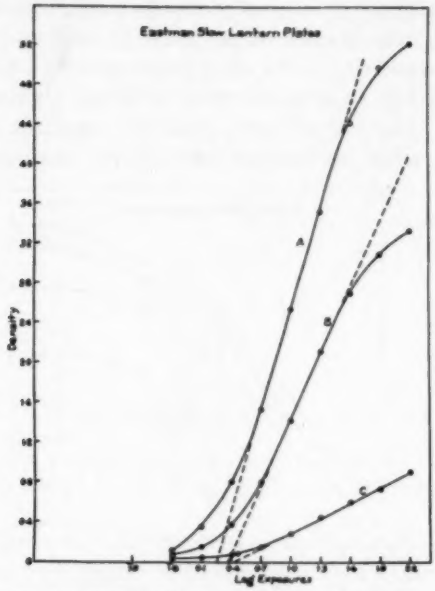

FIG. 12. *Characteristic curves for different intensities.* *A*—1280 mc, *B*—.020 mc, *C*—.000076.

TABLE 4. *Eastman Slow Lantern Plates*

DENSITY

log *I*	*I* · *t*								
	160	80	40	20	10	5	2.5	1.25	.625
3.9	.90	.73	.59	.43	.27	.15	.06	.04	.02
4.5	1.55	1.27	1.02	.75	.46	.23	.10	.06	.03
3.1	2.20	1.89	1.61	1.20	.79	.39	.18	.09	.04
3.7	2.79	2.53	2.20	1.65	1.11	.59	.26	.12	.06
2.3	3.32	3.07	2.73	2.07	1.42	.80	.37	.15	.07
2.9	3.79	3.54	3.20	2.46	1.71	1.00	.48	.19	.08
1.5	4.16	3.94	3.60	2.80	1.96	1.17	.59	.24	.09
0.1	4.49	4.24	3.95	3.11	2.20	1.31	.70	.30	.10
0.7	4.76	4.49	4.16	3.36	2.41	1.46	.78	.35	.12
1.3	4.94	4.68	4.30	3.53	2.55	1.56	.85	.38	.12
1.9	5.06	4.82	4.38	3.60	2.60	1.60	.88	.40	.13
2.5	5.16	4.92	4.42	3.60	2.60	1.59	.86	.38	.12
3.1	5.20	4.96	4.42	3.57	2.56	1.55	.80	.35	.11

Preliminary data on this subject are given here. A group of 20 strips was exposed at each of eight different intensities. Two or three of the strips from each intensity were combined so as to give several complete "runs" which were developed for times of from 2 to 20 minutes. From the densities of these strips the various characteristic curves were plotted, and from them, density-time of development and gamma-time of development curves. Data from these were finally used to plot the density-log I curves and the gamma-log I curves shown in Figs. 13 and 14. Fig. 13 shows the variation in density, all the curves being for an exposure of 5 mcs. For 2 minutes development there is very little failure, and optimal intensity is about 0.20 mc. When the development is carried to 20 minutes there is a great increase in the amount of

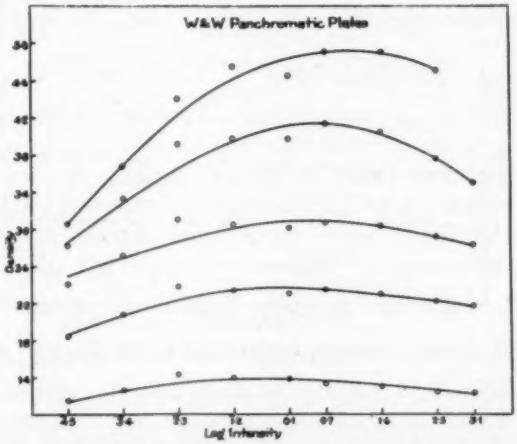

FIG. 13. *Variation of density with intensity for different development times. Constant $I \cdot t = 5$ mcs.*

failure, and the optimal intensity comes at about 20 mc or a shift of 100 times the lower value. A study of the curves shows that apparently the low intensity and high intensity exposures reach their maximum more quickly than the intermediate intensity exposures, which continue developing and thus increase the difference existing at shorter development times. Fig. 14 shows the variation of gamma with intensity for different development times. Gamma is practically independent of intensity for the two minute development, but a progressive increase with increasing intensity shows at 4 minutes. An optimal intensity appears at long development times. At 20 minutes its value is 300

meter candles. It is possible that the optimal intensity for density at high exposure values will reach this same value but the present experiments do not definitely settle this point. They do show, however, that the effect of development time is important not only on the position of optimal intensity but on the amount of the failure itself.

DISCUSSION OF RESULTS

The mathematical expressions most widely applied to reciprocity failure are those due to Schwarzschild and Kron. Recently E. A. Baker[6] has published data in which a special formula was built up for work on

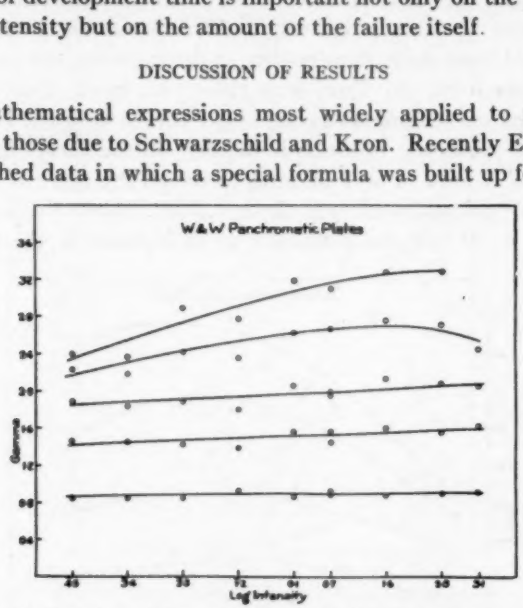

FIG. 14. *Variation of gamma with intensity for different development times.*

the color temperature of stars. He shows that his equation holds only over a very limited intensity range of about 1-100, and only for specular densities less than one; this corresponds to diffuse density of about 0.70. Since the values found here are all diffuse density, and for the most part greater than 0.70 his equation is not applicable to the present problem.

The work of Schwarzschild[7] led to the well known form

$$E = It^p \qquad (1)$$

where p is given as a constant which varies with different emulsions. Different observers vary widely in the values obtained, but most of them have reported some variation in its value when any very great range of intensity was used. It is interesting to note that the law given

[6] E. A. Baker, Proc. Roy. Soc. Edinburgh, *45*, p. 165; 1924-25.
[7] Schwarzschild, Astrophysical Jour., *11*, p. 89; 1900.

above was developed for use in determining star magnitudes when the method of extra-focal images was used.[8] This, of course, means that the illumination of the star images on the photographic plate is very low. Schwarzschild's laboratory data were also obtained at relatively low intensities, the shortest exposure being 3 seconds, and only low densities being reached. As was shown by Kron and Halm (loc. cit.) the true behavior of the photographic plate is not given for all intensities by this equation, but this equation approaches closely to the correct law at low intensities, at least under the circumstances which would ordinarily hold in astronomical work.

Kron represented his results by the form

$$E = I \cdot t\, 10^{-a\sqrt{(\log I - \log I_0)^2+1}} \tag{2}$$

The usual method of applying this is to use the logarithmic form

$$\log It = \log E + a\sqrt{(\log I - \log I_0)^2+1} \tag{3}$$

which represents a hyperbola convex toward the log I axis, with the vertex at log I_o, the illumination at which the energy (log It) is a minimum for the constant density for which the curve is drawn. As Kron shows, his results are very closely given by this formula, which reduces, as was pointed out by Ross,[9] at low intensities to Schwarzschild's law with the relationship between the constants

$$p = 1/(1+\alpha) \tag{4}$$

and at high intensities with the relationship

$$p = 1/(1-\alpha) \tag{5}$$

Kron also suggests two other less well known expressions for the reciprocity failure

$$\psi(I) = \frac{I^{\alpha+1}}{a+I^{\beta}+I^{-\beta}} \tag{6}$$

or, in the logarithmic form

$$\log (It) = \log \left[a + 2\cosh (M^{-1}\beta \log I) \right] - \alpha \log I + d \tag{7}$$

where M = modulus of common logarithms.

[8] Ross, The Physics of the Developed Photographic Image, Monograph No. 5, Eastman Kodak Co., p. 70.

[9] Ross, F. E., loc. cit., p. 64.

This equation represents a catenary in place of the hyperbola. Kron did not find this as satisfactory as the first form, and suggested another which may be called a generalized catenary

$$\psi(I) = \frac{1}{I^{\alpha-1}+I^{-\beta-1}} \tag{8}$$

or

$$\log(It) = \log(I^{\alpha}+I^{-\beta})+d \tag{9}$$

This form is also symmetrical with respect to the minimum point, and, when α and β are equal, is the same as (7).

Halm[10] is, so far as is known, the only one who has applied the catenary to any great extent. He made use of it in an extensive series of photographic measurements of star magnitudes, basing his preference solely on the fact that the catenary reduces at extreme intensities to Schwarzschild's law. He starts with the form

$$\log(It) = \log(aI^{\alpha}+bI^{-\alpha})+\text{const.} \tag{10}$$

and reduces it to

$$i_T = \tfrac{1}{2}[i^{\alpha}+i^{-\alpha}] \tag{11}$$

by the substitutions

$$i = \frac{I}{I_0} \qquad T = \frac{t}{t_0} \tag{12}$$

where I_0 is the optimal intensity and t_0 the time of exposure at optimal intensity necessary to produce the density for which the curve is drawn. By substituting the values (12) back in (11) and taking logarithms of both sides, we have

$$\log(It) = \log\tfrac{1}{2}\left[\left(\frac{I}{I_0}\right)^{\alpha}+\left(\frac{I}{I_0}\right)^{-\alpha}\right]+\log(I_0t_0) \tag{13}$$

which is the most convenient form for plotting and calculation. Comparing the fundamental photometric definition of star magnitudes

$$\log I = -0.40m+\text{const.}$$

when Kron's catenary form and Schwarzschild's expression are substituted he shows that at extremely low intensities the relationship between p and a is

$$p = 1/(1+a) \tag{14}$$

which is exactly the same as developed for the hyperbolic form (4). Thus the reasoning which led Halm to use the catenary is shown to be

[10] Halm, J., loc. cit., also ibid., *78*, p. 379; 1918; and *82*, p. 472; 1922.

erroneous, and his choice must therefore be considered purely arbitrary, since he states "According to Kron's calculations the former (hyperbola) would seem to render somewhat better justice to the observations than the latter (catenary)," but considers (14) sufficient to offset the slight advantage.

It is interesting to note graphically the difference between these three forms when drawn as if applied to experimental data. This is done in Fig. 15, where the Schwarzschild expression is the asymptote of both the catenary and hyperbolic functions of Kron. As can be seen,

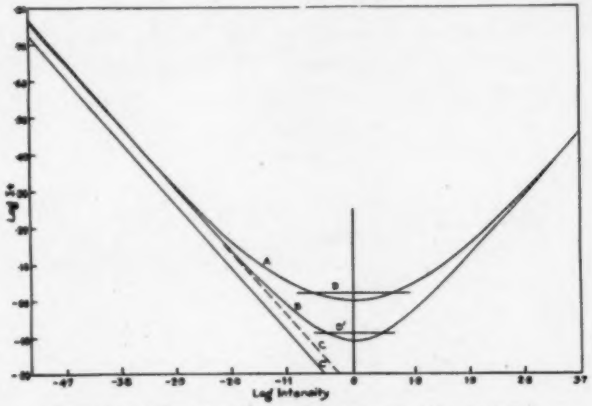

FIG. 15. *Relation of different expressions for reciprocity failure.*

A—Catenary } Kron
B—Hyperbola }

C — } Schwarzschild
C′— }

D — } Bunsen and Roscoe (reciprocity)
D′— }

these latter forms (A and B) check very closely at intensities less than 1/100 of optimal intensity. Over about the same range both are very close to the straight line representing the Schwarzschild equation. The line C' in the figure is the asymptote to the two curves, but if the equation were fitted to experimental data it would naturally be shifted to the position of C.

For intensities greater than .01 optimal, the catenary deviates farther from Schwarzschild's equation than the hyperbola. This curve, being much flatter, leads to a considerable range over which the reciprocity law holds accurately. The latter is represented by a straight line parallel to the log intensity axis, since the efficiency of all intensities

should be the same according to the reciprocity law. The line D shows the range over which it would hold in the region of optimal intensity, the ends marking the limit beyond which the error is greater than 0.02 in the value of log It. There is a range of 1 to 80 in intensity over which the reciprocity law holds within 5%. With Kron's usually accepted form this is reduced to a range of 1 to 16, as shown in D', while with Schwarzschild's expression the range is only about 1 to 2, with the same accuracy. These figures are only for the given value of 0.20 for a which gives a value of 0.833 for p from (4) and (14). If the failure is less, that is, if a becomes smaller, the range over which the reciprocity law will hold with sufficient exactness is increased in all cases. The marked differences would still be apparent, however. In the figure, if the asymptote to the curves is drawn on the high intensity side of the

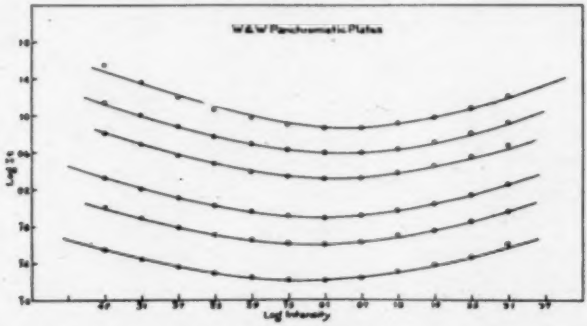

FIG. 16. *Constant density curves.* o— *experimental,* — *calculated, from data in Table 5.*

minimum, the relation (5) holds, leading to a value for p of 1.25. Experiments conducted between these limits will of course lead to intermediate values with the value $p=1.00$ at optimal intensity. This variation was pointed out in the first paper on this subject[11] and has been checked by the results of other observers, who must be working too close to optimal intensity to obtain accurate results with this expression.

APPLICATION TO PRESENT DATA

The application of the foregoing expressions to the data of this paper is given in Figs. 16, 17, 18, and 19. The curve best representing the experimental data has been found to be the catenary, this giving a far better fit than the hyperbola, while the Schwarzschild expression

[11] L. A. Jones and E. Huse, loc. cit., p. 1107; 1923.

is entirely useless except for a very limited range of intensities. Fig. 16 shows the constant density curves for panchromatic plates. The points, taken from characteristic curves drawn from the data of Table 1, are given in Table 5 together with the constants of Kron's law as applied. As can be seen, the curves fit the data excellently over the entire range. At the highest density, 2.8, the low intensity range does not check very well, but in no case is the deviation greater than 10% in the value of It and this value is reached only for the low intensity range of the curve for highest density and the high intensity end of the curve for the lowest density. As will be seen from Table 5, there is a progressive

TABLE 5. *W. & W. Panchromatic Plates*

LOG EXPOSURES

log I	Density					
	2.8	2.4	2.0	1.4	1.0	0.6
3.1	1.18	+0.91	+0.65	+0.25	$\bar{1}$.97	$\bar{1}$.61
2.5	1.09	.82	.54	.13	.85	.47
1.9	1.00	.72	.45	.04	.75	.37
1.3	0.90	.63	.37	$\bar{1}$.96	.68	.29
0.7	0.86	.59	.32	$\bar{1}$.91	.63	.24
0.1	0.85	.58	.30	$\bar{1}$.89	.59	.19
$\bar{1}$.5	0.90	.62	.34	$\bar{1}$.91	.60	.20
$\bar{2}$.9	0.98	.68	.39	$\bar{1}$.95	.64	.21
$\bar{2}$.3	1.07	.77	.47	0.01	.69	.28
$\bar{3}$.7	1.20	0.89	.57	0.10	.78	.36
$\bar{3}$.1	1.33	1.00	.69	0.21	.88	.42
$\bar{4}$.5	1.55	1.14	.81	0.32	.99	.57
log I_o	0.49	.43	0.28	0.00	$\bar{1}$.85	$\bar{1}$.74
log t_o	.37	.15	0.02	$\bar{1}$.89	$\bar{1}$.75	$\bar{1}$.46
a	.24	.22	.215	.20	.20	.19

increase in the value of log I_o, with increasing density, as well as an increase in the value of a, which shows the amount of failure. From the data obtained on the increase of failure with development time it is obvious that the relations given in Table 5 hold only for the particular exposure and development conditions used, namely, light of color temperature 2500°K with five minutes development at 68°F in pyro developer.

The application of Kron's catenary formula to the data for orthochromatic plates is given in Fig. 17, the characteristic curves being replotted from the data of Table 2. The data given in Table 7 were

then taken from these curves giving the log It value for different densities and for illuminations in steps of log $I=0.60$. The points were then plotted for the curves of constant density in Fig. 17 and Kron's law applied as shown by the continuous curves. A value of $a=0.21$ was found to give a satisfactory check in all except the lowest curve

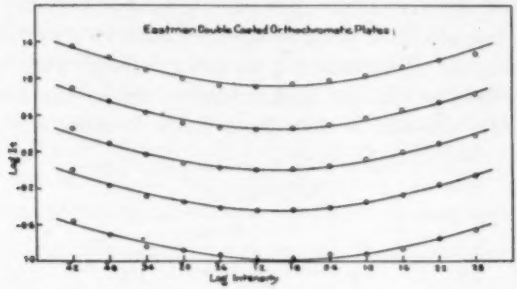

FIG. 17. *Constant density curves.* ○ *experimental,* — *calculated, from data in Table 6.*

(D = .40) where $a=0.20$ was used. The value of optimal intensity is 0.32 mc as found for the constant exposure curves of Fig. 6. As can be seen the curves follow the experimental points closely with no systematic deviations.

TABLE 6. *Eastman Double Coated Orthochromatic Plates*

LOG EXPOSURES

log I	Density				
	2.8	2.2	1.6	1.0	.4
2.8	1.27	.83	.38	−.06	− .66
2.2	1.20	.74	.29	−.16	− .75
1.6	1.11	.65	.19	−.27	− .87
1.0	1.03	.56	.11	−.35	− .93
0.4	.98	.49	.04	−.41	− .94
$\bar{1}$.8	.94	.45	.01	−.44	− .98
$\bar{1}$.2	.91	.44	.00	−.45	−1.00
$\bar{2}$.6	.93	.46	.02	−.42	− .94
$\bar{2}$.0	1.00	.51	.07	−.36	− .89
$\bar{3}$.4	1.09	.63	.17	−.29	− .84
$\bar{3}$.8	1.23	.75	.29	−.17	− .71
$\bar{4}$.2	1.35	.90	.45	.00	− .56
Log I_o	$\bar{1}$.50	$\bar{1}$.50	$\bar{1}$.50	$\bar{1}$.50	$\bar{1}$.50
log t_o	1.42	0.94	0.49	0.05	$\bar{1}$.50
a	.21	.21	.21	.21	.20

Turning to the two slow emulsions tested, we find that the agreement between Kron's catenary formula and the experimental data is not so good as with the higher speed emulsions. Table 7 shows the data for the constant density curves for the slow lantern plates obtained as in the previous cases. As can be seen, the value of log I_o progressively

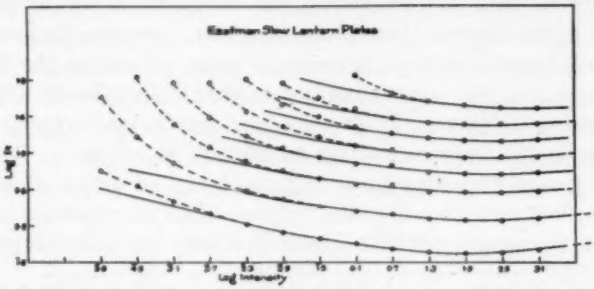

FIG. 18. *Constant density curves.* —o— *experimental,* — *calculated, from data in Table 7.*

shifts to higher values with increasing density, but there seems to be no definite progressive change in the value of a, which varies from 0.17 to 0.14. Referring to the curves shown in Fig. 18, it will be noted that

TABLE 7. *Eastman Slow Lantern Plate*

LOG EXPOSURES

log I	Density							
	4.2	3.60	3.00	2.40	1.80	1.20	0.60	0.20
3.1	1.48	1.31	1.13	.95	.78	.58	.28	1.94
2.5	1.48	1.30	1.12	.95	.76	.56	.25	1.90
1.9	1.51	1.30	1.12	.94	.76	.56	.26	1.89
1.3	1.55	1.32	1.14	.96	.78	.57	.27	1.91
0.7	1.63	1.37	1.20	1.02	.85	.65	.32	1.94
0.1	1.83	1.47	1.27	1.07	.87	.65	.35	0.00
1.5		1.59	1.38	1.16	.94	.71	.40	0.05
2.9		1.75	1.51	1.28	1.04	.80	.49	.12
2.3			1.80	1.44	1.17	.90	.58	.20
3.7				1.76	1.38	1.05	.70	.32
3.1					1.76	1.30	.88	.46
4.5						1.82	1.16	.64
5.9							1.61	.80
log I_o	2.50	2.40	2.50	2.38	2.44	2.26	2.14	1.86
log i_o	2.98	2.89	2.62	2.55	2.32	2.36	2.12	2.04
a	.16	.16	.15	.16	.15	.14	.15	.17

the equation fits the observed data over an intensity range of about one to 500,000 at the low densities, but fits for a comparatively short range of 1 to 100 at the highest density, with intermediate values for the other curves. There is no evidence of any tendency to break away from the experimental data at the high intensity end, and optimal intensity has just been reached. Thus from 1280 meter candles down to .005 meter candles, these plates could be used according to Kron's catenary formula without appreciable error, providing the densities were quite low. It is interesting to note that Halm (loc. cit. 1922) uses an emulsion of this type in his work, and obtains photographs of stars as faint as the 11th magnitude on them. According to Ross[12] the intensity of an 11th magnitude star photographed with a 20-inch telescope is .0085 meter candles, slightly larger than the minimum intensity at which the accuracy of Kron's formula is sufficient with this emulsion.

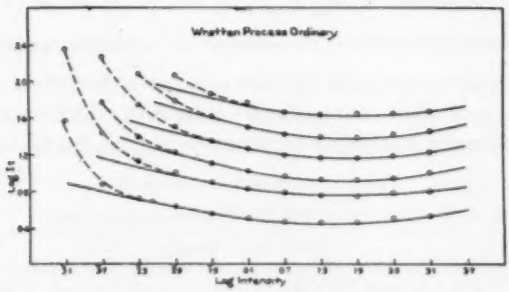

FIG. 19. *Constant density curves.* —o— *experimental,* — *calculated, from data in Table 8.*

Fig. 19 shows the curves for the slow ordinary plates. This is similar to the Lantern plate in the extent of agreement with the calculated curve, but the "break" is sharper at extremely low values of illumination. Referring to the curves of Fig. 3 it can be seen that this sharpness is also present in the case of the density-log I curves in contrast with the more gradual break in the case of Lantern plates. The highest density curves have a range of over one to 1,000 over which Kron's law is applicable, while with the lowest density there is no appreciable systematic deviation over a range of about one to 100,000. The greatest range used by Kron was one to 60,000, so the agreement with his formula at low densities is over a wider range of intensities than used when the formula was built up, even with these plates which deviate considerably from it at the lowest intensities.

[12] Ross, F. E., loc. cit., p. 70.

Using Kron's catenary expression in place of the usually accepted hyperbolic form, very satisfactory agreement between experimental and calculated data is obtained over a range of one to 8,000,000 in intensity with fast panchromatic and orthochromatic plates. With slow Lantern plates and Wratten Ordinary plates the agreement is satisfactory at high illumination levels but the curves do not agree at the extremely low intensity end of the scale, the experimental data showing a much greater failure of the reciprocity law than the calculated curves would indicate. Thus Schwarzschild's law would be invalid over any considerable range with the slow plates, while for fast plates it would hold satisfactorily over a somewhat greater range of low intensities.

TABLE 8. *Wratten Slow Ordinary*
LOG EXPOSURES

$\log I$	Density					
	2.8	2.2	1.6	1.00	.6	.2
3.1	1.67	1.45	1.23	1.00	.79	.52
2.5	1.65	1.42	1.18	.94	.78	.50
1.9	1.64	1.39	1.16	.92	.74	.45
1.3	1.63	1.39	1.16	.92	.75	.45
0.7	1.66	1.42	1.19	.96	.78	.46
0.1	1.76	1.49	1.26	1.02	.82	.50
$\bar{1}.5$	1.86	1.61	1.35	1.10	.89	.55
$\bar{2}.9$	2.06	1.78	1.50	1.22	1.00	.63
$\bar{2}.3$		2.08	1.74	1.39	1.12	.72
$\bar{3}.7$			2.26	1.77	1.43	.88
$\bar{3}.1$					2.35	1.51
$\log I_o$	1.90	1.85	1.77	1.80	1.80	1.45
$\log t_o$	$\bar{1}.71$	$\bar{1}.42$	$\bar{1}.38$	$\bar{1}.11$	$\bar{2}.96$	$\bar{2}.98$
a	.19	.21	.19	.20	.17	.17

Unless it has been definitely determined that the Schwarzschild relation holds to within the required precision for the particular photographic material and range of intensities used, no reliance should be placed on its validity. The experimental work involved in a verification of the applicability of the Schwarzschild expression under any given conditions is probably as great as that required for the determination of the constants of the Kron catenary expression which, according to our experimental work, is more satisfactory since it applies over a much greater range of intensities. In any problem of photographic

photometry involving a wide range of intensities, it is unsafe to assume the constancy of p in the Schwarzschild equation. This applies particularly to the average laboratory problem involving intensities of medium values. The Schwarzschild expression is quite valueless in the region of optimal intensities, which for the Eastman D. C. Orthochromatic plate is .3 meter candles increasing up to something greater than 1280 meter candles for the Eastman Slow Lantern.

As to the reason for the fact that Kron's second form fits our results far better than the first, while he has found the other form more satisfactory, we can not at present offer a definite explanation. The range of emulsions used in both cases would seem to be sufficient to indicate that the difference is not so much in emulsions as in the other experimental procedure. Kron, in a replotting of Schwarzschild's data[13] shows that a greater deviation from the Schwarzschild expression is found when pyro developer is used than when rodinal is the developing agent. Kron used rodinal in all his experiments while we employed pyro. This may account for a considerable part of the difference in form. The effects of different developing agents and different development times are being considered further in this laboratory.

It seems probable that a more complete understanding of the reciprocity relation may throw considerable light upon the fundamental nature of the latent image and its formation. A knowledge of the time-intensity function of single grain layer coatings, of known grain size-frequency distribution and grain sensitivity characteristics, and of materials sensitized and desensitized by specific methods should be particularly valuable for this purpose. Work along these lines is at present in progress in this laboratory.

A study of the results reported in this paper and the two previous papers of this series indicates that there is a more or less definite relation between the type and magnitude of the reciprocity failure and the speed or sensitivity of the materials. The relatively fast materials such as Seed 30, Double Coated Orthochromatic, Graflex, Motion Picture negative film, etc. show only a slight variation in the density resulting from a constant exposure over an enormous intensity range. These materials do not show any definite dependence of gamma upon intensity. The slower materials such as Eastman Slow Lantern, Wratten Slow Ordinary, and Motion Picture Positive film on the other hand give a great density variation for constant exposure and show a marked dependence of gamma upon intensity. For materials of medium speed

[13] Kron, E., loc. cit., p. 66.

such as W & W Panchromatic, Seed 23, etc., the magnitude of the density and gamma variation is of intermediate value. Furthermore the optimal intensity, I_o, is in general low for the high speed materials and high for those of low speed. This is in accordance with the findings of other observers.

The behavior of any photographic material necessarily depends upon the characteristics of the units of which it is composed, the individual silver halide grains. All of the materials on which we have published results thus far are standard commercial products in which the variation in size of the silver halide grains in some cases is small, and in other cases relatively great. The emulsion coating is usually thick and consists of several layers of silver halide grains. The grain size characteristics of such materials have been studied in detail in this laboratory,[14] and it has been found that in general the high speed materials have a rather large average grain size, and a broad distribution of grain sizes. The slow speed materials, however, have a much smaller average grain size and a much narrower size distribution. This indicates that high sensitivity is associated, in a general way, with large grain sizes, at least when sensitivity is defined in terms of the ability of a material to produce density.

It may be well at this point to call attention to the different senses in which this word *sensitivity* is used. As applied to the individual grain *sensitivity* must be expressed in terms of the amount of energy required to make the grain developable. Sheppard[15] words the definition as follows, "The reciprocal of the energy required to make a grain developable by a developer of given reduction potential." *Sensitivity* when applied to a photographic material as a whole must be expressed in terms either of the density made developable by the action of a fixed amount of energy or in terms of the energy required to make developable a given density. The usual determinations of plate "speeds" are based upon the latter definition of sensitivity.

Since there is evidence that grains of the same size may have different sensitivities (grain sensitivity) it is not permissible to assume that the sensitivity distribution function is identical in shape with the grain size frequency curves. It seems reasonable, however, to believe that they are of the same general type.

It seems to be well established that gamma is intimately associated with homogeneity of grain sensitivity, high gamma indicating a

[14] Wightman, Trivelli, and Sheppard, J. Phy. Chem., *27*, p. 1-51; 1923.
[15] Wightman, Trivelli, and Sheppard, J. Frank. Inst., p. 458; Oct. 1922.

relatively small variation in the sensitivity of individual grains. So far as the materials which we are considering are concerned, this homogeneity of sensitivity seems to be closely associated with homogeneity of grain size. The fact that we have observed a great decrease in gamma at low intensities in the case of the slow materials indicates that at low intensities the distribution of grain sensitivity is effectively broader than at high intensities. As stated previously the characteristics of a photographic material are dependent upon the characteristics of the individual units of which it is composed. It follows that when such a material departs from the reciprocity law some or all of the individual grains composing that emulsion must depart from the reciprocity law. Since our observations show that materials of high sensitivity have a low optimal intensity and materials of low sensitivity have high values of optimal intensity, it seems logical to assume that individual grains of great sensitivity have a low value of optimal intensity and those of low sensitivity a high value. The term "optimal intensity" as used in reference to an individual grain has a somewhat different significance than when applied to the material as a whole. In the case of the grain it must be defined as that intensity (rate of application of energy) at which the minimum quantity of energy will produce developability. In case of the material as a whole optimal intensity is defined as that intensity at which a fixed quantity of energy produces the maximum density. Thus in the case of the grain, the criterion by which optimal intensity is defined is *developability* while in the case of the material as a whole it is *density*. On the basis of the assumptions relative to the optimal intensity values of grains of different sizes and sensitivities it is possible to explain the decrease of gamma observed in the case of slow speed materials. As previously stated these materials have a relatively narrow distribution of grain size or sensitivity. The curve showing the relation between frequency and grain size is not symmetrical but is of the skew probability type in which the average size is greater than the size of maximum frequency, thus giving a curve which tails off more gradually in the direction of large grain size than in the small grain size direction. When the intensity is decreased progressively below the optimal intensity for the material as a whole, it approaches the values of optimal intensity for the larger and more sensitive grains, thus making these classes more effective in contributing to density. The same progressive lowering of intensity makes the departure from the optimal intensity of the less sensitive and smaller grain classes greater and greater, thus rendering them more and more

ineffective in producing density. The net result of this is that the effective breadth of the sensitivity or size distribution is increased, which we know from analogy should lead to lower gamma values. In the case of high speed emulsions the sensitivity distribution is apparently so broad that a great variation in intensity does not produce a further effective broadening and hence no gamma variation is observed.

The assumption of various optimal intensity values for the individual grains differing in sensitivity also makes it possible to explain the relatively large variation in density, resulting from a fixed exposure in case of those materials having relatively narrow sensitivity distribution, such as the low speed emulsions studied; and the same assumption explains the relatively small density variation observed in case of those materials having relatively broad sensitivity distribution such as the high speed emulsions. Furthermore this affords a satisfactory explanation for the observed increase in optimal intensity with increasing exposures.

SUMMARY

1. Data on the reciprocity failure have been obtained for four plates, W. and W. Panchromatic, Eastman Double Coated Orthochromatic, Wratten Slow Ordinary, and Eastman Slow Lantern.

2. The density-log I curves for the Panchromatic and Orthochromatic plates show a definite optimal intensity with a larger drop at extreme intensities than is the case with the fast ordinary emulsions previously studied.

3. The Process and Lantern plates have their optimal intensity at very high values with an enormous drop in density at low intensities.

4. Gamma is independent of intensity for Orthochromatic and varies only slightly with Panchromatic, but drops to very low values at low intensities for the other two emulsions.

5. An increase in the development time of Panchromatic plates increases the amount of failure of both density and gamma, and shifts optimal intensity to higher values.

6. Results thus far indicate that in general high speed emulsions, in which the average grain size is relatively great, have a relatively low value of optimal intensity; while low speed emulsions, in which the silver grains are much smaller and in general much more uniform in size, have much higher optimal intensities. The dependence of gamma upon intensity is much greater in the case of the low speed fine grain materials.

7. As an empirical formula Kron's catenary form

$$\log It = \log \tfrac{1}{2}\left[\left(\frac{I}{I_0}\right)^{a} + \left(\frac{I}{I_0}\right)^{-a}\right] + \log I_0 t_0$$

has been found to fit the results excellently for the higher speed materials and at high intensities for the slow materials.

EASTMAN KODAK CO.,
ROCHESTER, N. Y.,
OCTOBER, 1925.

Resonance-Lines of Neon.—Hertz employs Lyman's technique of ultraviolet spectroscopy for locating these lines: a concave grating at one end of a long tube, the slit and the photographic plate at the other end, a low-voltage arc operating near the ionizing-potential of Ne placed just behind the slit; no solid screen separates the arc-chamber from the main tube, but by a properly-placed outlet to a pump the pressure in the latter is maintained at about 0.3 mm while the pressure around the arc is 4.5 mm. Two lines were distinctly photographed (there is a a good picture in the article) being at 735.7 and 743.5A respectively, with uncertainty (to be diminished later) of 0.5A. Their frequency-difference shows that they are combinations with the terms $1s_2$ and $1s_4$; hence the normal state of the neon atom is a p-state. From the presence of these lines and the absence of combinations with $1s_3$ and $1s_5$, it follows that $j=0$ in the normal state; also that the $1s_3$ and $1s_5$ states are metastable, which agrees with much experimental evidence of diverse character (cf. This Journal *11*, p. 146). The value of the fundamental term is 173970 ± 100; the two ionizing-potentials (corresponding to two distinct states of the atom minus one electron) are 21.47 and 21.57 in good agreement with direct measurements (cf. This Journal, *8*, pp. 801-802).—[G. Hertz, Eindhoven; ZS. f. Phys. *32*, pp. 933-939; 1925]. KARL K. DARROW

Influence of Magnetic Field and of Admixed Gases on the Emission Spectrum of Iodine.—Long descriptive paper giving the impression that the phenomena are very complex and confusing. The magnetic field elicits certain entirely new lines in the discharge-spectrum, suggesting that it effects a profound alteration in the molecule; some spark lines are broadened by the field, but the sharpness of the lines produced by a high-voltage direct current is not affected by it. Admixed gases diminish the intensity of the iodine spectrum very greatly, without themselves emitting any notable amount of radiation. Experiments with a small quantity of He and Ne mixed into the iodine vapor showed that the iodine lines were rendered much sharper, sometimes resolved into two or three components, by reason of the added gas; some lines that with the pure vapor could hardly be obtained at all were strongly brought out.—[W. Steubing, Aix-la-Chapelle; ZS. f. Phys. *33*, pp. 113-127; 1925]. KARL K. DARROW

INSTRUMENT SECTION

THE RADIATION POTENTIOMETER

By Donald C. Stockbarger

The purpose of this paper is to present the principle of a potentiometer device for use in radiometric work. The actual design of the instruments themselves will not be considered because they are still being developed with a view of obtaining a portable set of sufficient accuracy for ordinary technical work.

The principle of the analysis is not new. It has been employed by Coblentz[1] and others, and has been in use in this laboratory for several years. It consists in measuring, by means of a thermopile and galvanometer, the radiant energy lying between rather widely separated spectral limits by difference, employing suitable calibrated filters for this purpose. For example, by measuring the radiant energy between 2000A and 4000A and between 3000A and 4000A, the energy between 2000A and 3000A can be calculated. Similarly smaller regions can be studied.

Although it is theoretically possible to do accurate work by this means, practically it is often difficult to obtain even approximately correct results. The reason for this is that if the intensity of the source is varying rapidly no comparison can be made between readings of total and filtered radiation intensity taken a few seconds apart. To illustrate what the difficulty really is, we may consider the case of a flaming arc. Fig. 1 shows how the total radiation intensity of a G. E. luminous arc varies with time. Obviously, to attempt to obtain an average value of this intensity by a thermopile and galvanometer would be practically hopeless. Even if an average were obtained over a given period, say 10 minutes, this average would not be correct during the next period during which the intensity of filtered radiation was being measured, and therefore no comparison could be made. If a single reading were taken of the total intensity, the filter inserted in the path of the radiation and a second reading taken, the second might easily be about equal to or considerably greater than the first. Actual experience in the laboratory has repeatedly confirmed these statements. If time is no factor, a large number of alternate readings may be taken

[1] Coblentz, Long, and Kahler, Bur. Stds. Sci. Paper No. 330; 1918.

and the means regarded as the true values, but when the source is of short life the method fails.

The use of an ordinary potentiometer to measure the voltages corresponding to the different intensities is out of the question on account of the time required to obtain a balance. It is obvious, however, that if a standard cell could be devised whose voltage would rise and fall with the intensity of the source, the potentiometer would be an ideal instrument for this purpose. Although we have no such standard cell,

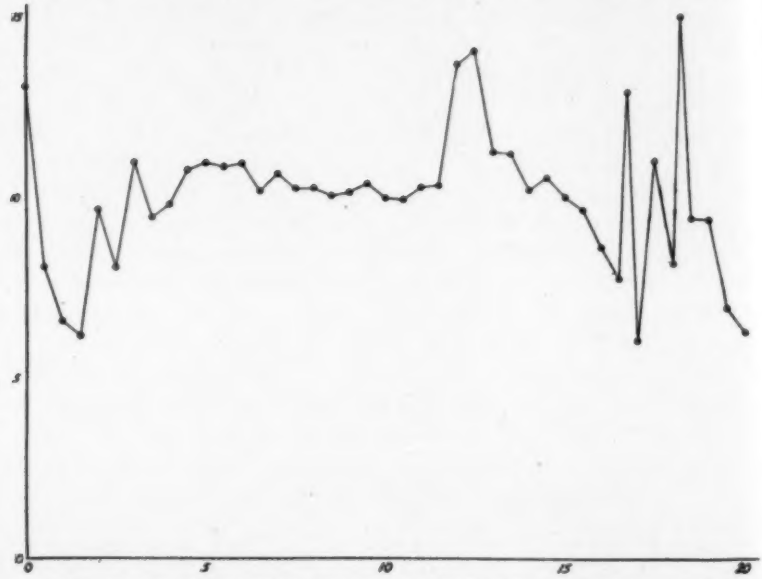

FIG. 1. *Intensity of total radiation from a G. E. 4 ampere, form 3, luminous arc as a function of time. Long life electrode. Clear glass globe. Abscissas: minutes. Ordinates: centimeters galvanometer deflection.*

we can substitute a thermopile of correct design and allow total radiation to fall upon this while the radiation from a smaller spectral region falls upon the analyzing thermopile. This has been done with considerable success. Not only is it possible to study badly fluctuating arcs, but routine measurements on ordinary sources can be made much more rapidly than by the old methods.

Fig. 2 is a simplified diagram of the apparatus. T_1 is the standard thermopile which is mounted in the same case with, and close to, T_2 which is the analyzing thermopile. R_2 is the potential resistance wire

the voltage drop across which can be adjusted by the variable resistance R_1. R_3 is a resistance slide wire similar to R_2. If the resistances of R_2 and R_3 be chosen properly the galvanometer will remain critically damped whatever the setting of the slider S. To obtain an initial balance the slider is set at "100," i.e., right hand end of R_2 and R_3, and then R_1 is varied until the galvanometer does not deflect when a shutter is raised and lowered in front of the instrument. If now a filter be placed in front of T_2 and a new balance obtained by moving S, the reading on the scale under R_2, opposite the indicator on S, will give directly the ratio of intensities falling upon the thermopiles. This must, of course, be corrected for reflection and absorption losses due to the filter employed.

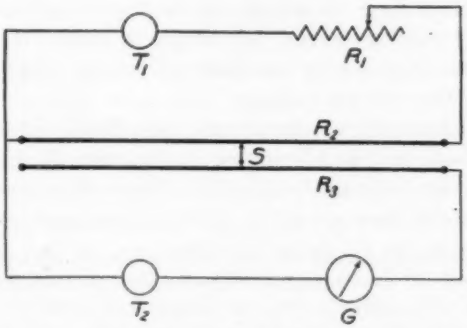

FIG. 2. *Simplified diagram of radiation potentiometer circuit.*

Referring again to Fig. 1, suppose that the "standard" thermopile is producing a voltage which follows the intensity curve, and suppose that the filter over the analyzing thermopile cuts off 50 per cent of the total energy. Then the voltage produced by the latter thermopile would at all times be one-half that produced by the former, and the potentiometer would balance with the slider at "50" whether the observation was being made at the end of 1.5 minutes or 12.5 minutes, assuming that the energy distribution was the same at both times.

In general, however, the energy distribution is not constant when the intensity is changing, and therefore the behavior of the apparatus is not as simple as would at first be supposed. There are two factors which tend to make the intensity of an arc vary, viz., unsteady line voltage and instability of the arc. Taking a stable quartz mercury arc as an example, if the line voltage be suddenly increased the current will increase immediately while the arc voltage will increase very slowly due

to the time required to raise the temperature of the arc. The current will decrease to approximately its original value provided that no further line voltage changes occur in the meantime. The reverse of this process will take place if the line voltage be suddenly decreased. The intensity of the radiation is affected more by a change in arc voltage than by one in current, as has been shown by Harrison and Forbes[3] and as will be shown by the writer in a later paper, so that if the line voltage be increased there will be a resulting sudden increase in total radiation intensity followed by a slow increase as the arc voltage grows. The flickering due to instability is the result of rapid arc voltage and current variation of opposite sign. At one instant the arc voltage is too high and the current too low; at another, the reverse condition exists. The magnitude of these variations may be 5 or 10 per cent or more and the frequency may be several per second or only a few per minute. The power does not remain constant, indicating that the current is varying more than the arc voltage.

Because the intensity of mercury arc radiation in general is affected more by arc voltage than by current, and because the individual lines do not all increase in intensity equally, it follows that the energy distribution cannot be constant for a flickering mercury arc. Probably similar reasoning can be applied to other arcs. In fact no demonstration is required for flaming arcs whose visible radiations are not constant in color, although varying salt vapor composition is here largely responsible for the fluctuation in energy distribution. It is well known also that the energy distribution of radiation emitted by an incandescent solid is a function of the temperature and hence of the total radiation intensity.

In any of these cases there can be no exact analysis and therefore an average value must suffice. If the frequency of the variations in intensity is not too high the galvanometer deflection will not be zero when the potentiometer slider is correctly set but it will oscillate between small plus and minus values. The closeness with which these oscillations follow the fluctuating of the source will depend upon the period of the galvanometer as well as the thermopile response time. A very little practice enables the operator to set the slider at the best position and therefore to obtain a good average value.

It often happens that the radiant energy distribution of a source fed with salt vapors, e.g., flaming arc, varies slowly so that the correct

[3]Harrison and Forbes, J.O.S.A. & R.S.I., *10*, p. 1; 1925.

"average" settings of the slider are not always the same. This slow variation is to be distinguished from the rapid variation which may be produced by ordinary flickering. The figures in Table 1 illustrate this point. Obviously here a mean value of the individual average settings should be regarded as the true value.

TABLE 1.—*Slider settings made several minutes apart for a badly fluctuating flaming carbon arc. A, quartz water cell over analyzer. B, quartz water cell and Noviol O glass over analyzer.*

A	*B*	*A*	*B*
37.2	19.8	39.4	19.0
38.4	19.8	38.0	22.6
37.2	22.0		23.6
38.4	20.6		23.6

If mechanical means of inserting and removing filters is provided, the ordinary method of analysis can be made to yield results which are as reproducible as those of the instrument herein described. Table 2 shows the results obtained on another fluctuating arc by means of a single thermopile. The procedure was to watch the galvanometer until momentarily it was nearly steady, to take a reading, quickly insert or

TABLE 2.—*Intensities of radiation emitted by a badly fluctuating flaming carbon arc measured in rapid rotation by means of a single thermopile and galvanometer. A, quartz water cell over thermopile. B, quartz water cell and Noviol A glass over thermopile.*

A	*B*	Ratio $\frac{A}{B}$	*A*	*B*	Ratio $\frac{A}{B}$
15.5	10.4	0.671	13.9	9.45	0.680
12.6	8.55	0.678	14.3	9.45	0.661
12.0	8.15	0.679	14.5	9.65	0.665
13.7	7.85	0.573	14.6	9.85	0.675
12.1	8.10	0.669	14.4	9.45	0.656
12.5	8.05	0.644			

remove the filter and take a new reading. If the latter deflection was readable, i.e., if the galvanometer appeared to be nearly steady, the arc probably had remained constant during the process. As the ratios in the table indicate, such is often the case. But an enormous amount of time is spent in waiting for favorable conditions, and a great many first readings are taken for which no second reading can be obtained. The radiation potentiometer would have made these measurements in a minimum of time.

Table 3 shows how closely the radiation potentiometer usually reproduces analyses made on a quartz mercury arc in which only the flickering due to instability comes into play. These analyses were each made in a few minutes. Probably at least a total of sixty galvanometer readings would have to be made for each of these analyses by the ordinary method in order to obtain such close agreement. Although comparatively little time would be lost between readings the total time required would be several times that consumed by the new method.

TABLE 3.—*Two sets of radiation potentiometer slider settings for the same quartz mercury arc operated under the same electrical conditions. A, quartz water cell; B, quartz water cell and G86B glass; C, quartz water cell and Noviol O glass over analyzer.*

A	*B*	*C*
54.8	33.4	19.1
54.8	33.3	19.1

It should be pointed out that the two thermopiles should be made as nearly identical in quickness of response as possible, for otherwise the intensity fluctuations might cause such uncertainty as to render the method useless. In the instrument now in trial use, the thermopiles are of rugged construction with the consequence that about 10 seconds are required for thermal equilibrium. The times of response differ by about one second. No attempt has been made to make these times equal because the behavior of the instrument has been satisfactory under the conditions to which it has been subjected during the preliminary work.

The entire external circuit has been constructed of copper and therlo, the thermoelectromotive force of which combination is low, in order to eliminate errors due to air currents around the apparatus.

The work on the radiation potentiometer has been made possible by financial aid received from the Cooper Hewitt Electric Company, Hoboken, New Jersey.

ROGERS LABORATORY OF PHYSICS,
ELECTROCHEMICAL DIVISION,
MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
CAMBRIDGE, MASSACHUSETTS, October 14, 1925.

A SENSITIVE NICHOLS RADIOMETER

OTTO SANDVIK

During the course of an investigation of infrared arc spectra in vacuo, it was found necessary to increase the sensitivity of the Nichols radiometer as described by Spence (J.O.S.A. *6*, p. 625; 1922). The purpose of this article is to describe somewhat in detail the method of construction and characteristics of the radiometer finally adopted. Aside from high sensitivity, when a source of radiation falling upon a radiometer vane is not constant a radiometer with a reasonably short period is the desideratum. The period may be reduced either by the use of a comparatively heavy quartz fibre suspension which reduces the sensitivity or by constructing a radiometer system with a very small moment of inertia. The latter alternative must be chosen. The moment of inertia may be reduced by placing the vanes very close together or by reducing the mass of the system and that of the vanes in particular. The vanes cannot be placed too close together because the shielded vane may become subjected to incident diffuse radiation. The hope for increased sensitivity appeared to lie in decreasing the mass of the vanes.

CONSTRUCTION OF THE RADIOMETER SYSTEM

Aluminum leaf, such as that used by the gilder, was cut into narrow strips about 50 mm long. The strips, approximately 4.5μ thick, ranged in width from 0.15 mm to 0.4 mm. From a large number of these cuttings, suitable strips were selected, laid flat on a brass plate, and their ends fastened down by shellac. They were then blackened by exposing them to the soot of burning gum camphor. A pair of strips of approximately the desired width was selected and their ends fastened to two glass capillary tubes fastened parallel on glass and about 25 mm apart. The blackened surfaces of the strips were placed downward. Two pieces of the finest glass capillary tubing drawn from ordinary thin walled glass tubes about 3 mm long were placed across the aluminum strips about 15 mm apart. These cross pieces were fastened to the strips by shellac. A straight glass staff of fine capillary tubing about 6 cm long was laid across the two cross pieces midway between the strips and parallel to them. The staff was then fastened to the cross pieces by means of shellac. The system was complete with the exception of the mirror of thin glass about 1 mm^2, which was shellacked

to one end of the staff with its plane parallel to that of the vanes. The mirror was usually shellacked to the staff after the system was removed from the glass plate. The whole operation is exceedingly delicate and requires considerable technic.

As an illustration, the total mass of one of these systems was 1.63 mg; the masses of the glass staff and mirror were 1.123 mg and 0.192 mg respectively. The mass of the vanes which were 0.2 mm wide and 15 mm long was too small to determine on the ordinary chemical balance. Approximately 80% of the total mass of the system was in the glass staff, whose moment of inertia about a central axis parallel to its length was exceedingly small.

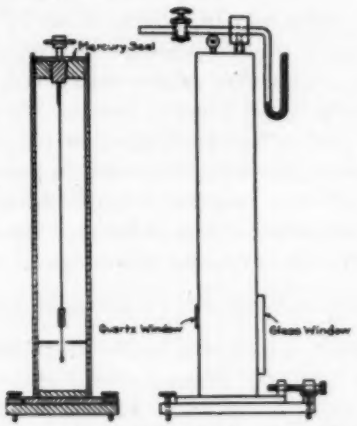

FIG. 1. *Front sectional and side view of the radiometer.*

The case in which the system was suspended was modified slightly from that previously described (loc. cit.). It was found in the earlier design that some stray radiation due to local heating of the case due to the source of light used to illuminate the mirror caused an uncertainty of the zero of the instrument. Accordingly, a diaphragm with a hole 1 cm in diameter was permenently inserted in the case so that when the system was suspended the plane of the disc was at right angles to staff and midway between the mirror and the lower ends of the vanes. This effectually shielded the vanes.

PERFORMANCE OF RADIOMETER

Westphal (ZS. f. Phys. *1*, p. 92; 1920) has made a careful study of the sensitivity as a function of the pressure. In every case, he found

a maximum sensitivity occurring at a pressure of about 0.021 mm of Hg. The writer made similar determinations and the results were in accord with those of Westphal. Table 1 and Fig. 2 illustrate the results with one of these radiometers.

It is interesting to compare the sensitivity of these radiometers with one used by Nichols (Astrophys. Jour. *13*, p. 101; 1901) for stellar radiation. The Nichols radiometer gave a deflection of 127 mm per mm² of exposed surface with a candle at a distance of 1 m and scale distant 1 m from the radiometer. Nichols stated that he did not

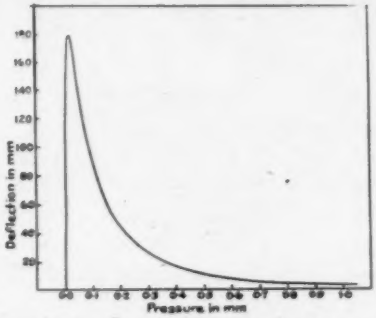

FIG. 2. *Change in sensitivity with the gas pressure.*

measure the pressure but remarks that he believed that it was that at which the radiometer had a maximum sensitivity. One of our radiometers which attained its maximum deflection in 2 minutes gave a deflection of 15000 mm per mm² for a Hefner lamp at a distance of 1 m. The bolometer used by Snow (Ann. der Phys., *47*, p. 208; 1892) in his work on sodium gave a deflection of 1.5 mm per mm² of exposed surface under conditions as described above.

TABLE 1.

p	*d*	*p*	*d*	*p*	*d*
1 mm	3.2	0.0765	113.1	0.0087	135.0
0.854	3.22	0.060	133.0	0.0061	118.0
0.67	6.62	0.047	151.0	0.0037	78.0
0.45	13.4	0.036	116.0	0.0010	13.9
0.35	21.7	0.027	177.0	0.00071	7.4
0.20	44.0	0.022	179.0	0.00032	1.4
0.12	77.4	0.015	174.0		
0.095	96.0	0.010	154.0		

More recently Tear (Phys. Rev., *23*, p. 641; 1924) described a type of radiometer differing radically in construction. Tear used short de-

hydrated mica vanes, 1 to 3 mm in length, and .2 to .5 mm wide. The experience of the writer leads him to the conclusion that vanes 10 mm long and 0.2 mm wide cannot be made from dehydrated mica. The longer and narrow vane has a distinct advantage for spectrum analysis.

It is of interest to compare radiometer No. 3 described by Tear, with two of our radiometers. Radiometer No. 3, having a period of 38 seconds and an area of 10 mm², is described as showing a deflection of 1400 mm per mm² of exposed surface. One of our radiometers, with vanes 10 mm long and .2 mm wide, indicated a deflection of 15000 mm per mm² of exposed surface, with a Hefner lamp and scale at a distance of 1 m from the radiometer. This radiometer required 2 minutes to attain its maximum deflection. This radiometer, too sluggish for spectrum analysis, would prove useful and remarkably sensitive for stellar radiation examination.

Another radiometer, which attained its maximum deflection in 14 seconds, gave a deflection of 1800 mm for a Hefner lamp and scale distant 1 m from the instrument. This corresponded to a deflection of 600 mm per mm² of exposed surface. No attempt was made to correct these results for absorption and reflection of the quartz window used on the radiometer.

This work was done in the Laboratory of Physics, Northwestern University, and the writer takes this opportunity to express his appreciation of the service of Mr. Kung, the mechanician.

ROCHESTER, N. Y.
APRIL, 1925.

Influence of Electron-Bombardment upon Photoemission from Al.—An aluminium plate was exposed, alternately and then simultaneously, to ultraviolet irradiation of fixed intensity and to a bombarding stream of 98-volt electrons. The current of slow electrons emerging from the plate when both agencies act together is in excess of the sum of the currents produced by each alone; thus the electron-bombardment seems to favor the detachment of internal electrons by the light. The percentage excess is greatest when the electron-bombarding-current is least; the absolute excess passes through a maximum. A striking result is this, that although aluminium is normally insensitive to light transmitted by glass, yet the Al plate while being bombarded by 98-volt electrons exhibited a marked increase in secondary-electron-emission whenever irradiated through glass; even red light was able to effect this. The paper is not as detailed as it should be; notably it is not quite clear what Dember defines as "secondary electron emission." —[H. Dember, Technische Hochschule, Dresden; ZS. f. Phys., *33*, pp. 529-532; 1925]. KARL K. DARROW

ATMOSPHERIC ABSORPTION AND TRANSMISSION IN SEARCHLIGHT PRACTICE

By R. M. Langer

Pioneer work on atmospheric absorption was done mainly for astronomical purposes or for the purely scientific end of determining the optical constants of air. For the first purpose the thickness of the atmosphere was taken and the only variations were to go to different altitudes (sea level − 5000 m), or to take observations at different angles with the vertical. The most complete work in this field was done by Abbot and Fowle and published in volumes 2, 3, and 4 of the Annals of the Astrophysical Observatory of the Smithsonian Institution. For the older work see: "Transparency of the Atmosphere," by C. Chistoni in Nuovo Cimento *12*, p. 35; July 1900; Atti della Societa dei Naturalisti e Matematici de Modena, Serie *3*, *16*, p. 165-187, in which the author summarizes the work of Bouguer, Pouillet, Violle, Maurer, Angot, Forbes, Crova, and Randan. More recently extensive bibliographies have been published by Fowle[1] and by E. Karrer and U. M. Smith.[2]

Laboratory experiments on absorption coefficients of air are always done under conditions very different from those obtaining in the field. Comparatively small chambers are used, convection is prevented, moisture is usually removed as well as dust, and the temperature and pressure are carefully regulated. The length of path is usually a few meters and the light source is of comparatively low intensity and is very steady. The interest usually attaches to the absorption bands which are apt to be in the ultraviolet or infrared, and therefore of no consequence in searchlight work. Then too it is frequently the relative absorption of different wave lengths which is measured while the total absorption is not regarded.

There are in the literature few references to a direct measurement of the total absorption coefficient of air for white light. The most direct is given by G. Gehlhoff u. H. Schering,[3] who set up a Beck arc, sent the beam along the ground, and took photometer readings up close and at about a kilometer's distance. Oddone (Winkelman, Handbuch

[1] J.O.S.A. & R.S.I., 7, p. 99; 1922.

[2] J.O.S.A. & R.S.I., 7, p. 1230; 1923.

[3] G. Gehlhoff u. H. Schering, "Ueber ein neues Photometer sehr hoher Empfindlichkeit und einige Anwendungen," Zeits. f. Techn. Phys. *1*. pp., 247-256; 1920.

d. Physik, *6*, p. 555) gives the value 97.4 per cent for the transmission factor of 1 km of clear dry atmosphere as determined by comparison of snow fields in the Alps. Abbot's data (Annals) permit a calculation of total absorption coefficient for sun light and the total atmosphere, and L. V. King[4] in an appendix (VII) to his paper gives some results of such calculations.

Since the war a number of papers more closely related to searchlight practice have been published especially on the basis of work done at the Bureau of Standards. Very interesting and important measurements were made by E. Karrer and E. P. T. Tyndall[5] and by E. Karrer and V. M. Smith.[6] It must be admitted, however, that a great deal more must be done before even the more immediate requirements of the Army or Navy service can be satisfied.

The whole problem of searchlight projection as concerned with atmospheric transmission can be put as follows: To find an expression for the visibility of an object in a searchlight beam as a function of all the independent variables. These are:

(1) The spectral composition of the light.
(2) The intensity of the beam at the source.
(3) The shape of the beam.
(4) Luminosity of the beam due to scattered light.
(5) Meteorological conditions, such as direction of air currents, turbulance, dust, fog, and rain conditions, etc.
(6) Physical conditions, and their changes with time and altitude.
(7) Altitude of the object.
(8) Distance to the object.

These topics will be treated in special paragraphs for each, but it will be impossible to treat one independently of all the others. A wealth of data is available with which useful calculations might be made, but for lack of any definite indication as to what would be especially important at the present time, and because of the amount of time required for such calculations, none were undertaken. Of course, if this work were to be useful in practice, it would have to be made up into tables and graphs, but it will be first necessary to carry out a great deal of research.

[4] Appendix to "Scattering and Absorption of Light in Gaseous Media," Phil. Trans. Roy. Soc., Series A, *212*, pp. 375-433; 1923.

[5] E. Karrer and E. P. T. Tyndall. Relative Spectral Transmission of the Atmosphere, Bul. Bur. of Standards, *16*, p. 377; 1920.

[6] E. Karrer and V. M. Smith. Diffusion of Light from Search light Beams, J.O.S.A., EcR.S. I., *7*, p. 1211; 1923.

(1) The spectral composition of the light source.

The spectral composition of the light used in searchlights has been investigated only to a very slight extent. Probably the most extensive work was done by Priest, Meggers, and their associates at the Bureau of Standards.[7] Their work showed the Sperry arc to be comparatively stronger in the blue and weaker in the yellow and red than the noon-day sun in Washington, in spite of the fact that they used only from forty to seventy amperes. The spectrum seems to consist of groups of bands characteristic of the material used in the carbon cores.

It is fairly certain that, V, the visibility of a target is an increasing function of, S, the sensitivity of the eye (relative photicity) and, of I, the intensity of the source (luminosity). Now from the well-known form of these functions (Fig. 1) we can draw some conclusions regarding

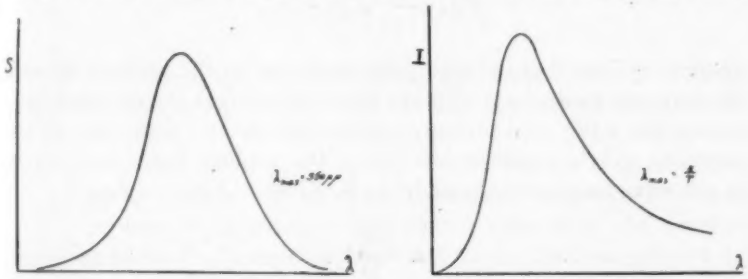

FIG. 1

the best temperature for the light source. The sensitivity curve has only one maximum which occurs at $\lambda = 555 m\mu$. As for I we will use the expression for a black body at high temperature and expect the conclusions to hold for an actual searchlight source. As justification for this procedure we may quote from the paper referred to above,[8] as follows: "The spectral distribution for equivalent color of a regular Sperry 45-volt, 75-amp. searchlight . . . . was found to be very close to that of the noon sun at Washington, i. e. approximately that of a 'black body,' at 6000°K." We may therefore consider the function I as having but one maximum at some wave length in the ultraviolet. If then the temperature of the source be raised, both the intensity and the spectral distribution are affected. Since increased temperature

[7] Published under the title "Color and Spectral Composition of Certain High Intensity Arcs," as Technical Paper 168, 14, p. 120 of the Bureau of Standards, and—in cooperation with the Searchlight Investigation Section, Corps of Engineering—published in the Phys. Rev., (2) *14*, p. 148, 1919.

[8] See preceding footnote, Phys. Rev., (2) *14*, p. 185; 1919.

causes increased intensity for all wave lengths and since $\partial V/\partial I > 0$ we see that aside from changes in distribution, increasing the temperature of the source improves the visibility of the target. But taking into account that S is fairly symmetrical to the line $\lambda = 555m\mu$ and that the curvature of I is convex upwards and increases with temperature, it can be proved that the change in distribution due to increase in temperature of the source is detrimental to the visibility of the target. It follows that there may be a temperature which is better than all others for a particular arc. What this temperature is cannot be found until V is known as a function of S and I.

The intensity of light from a point source in a homogeneous medium and of monochromatic frequency is

$$I(\lambda) = \frac{I_0(\lambda)}{r^2} e^{-a\lambda p \int_0^r \rho dr}$$

where a_λ is defined as the absorption coefficient of the medium for unit pressure and mass of gas, I_0 is the initial intensity, r the distance from the source, p the total pressure, and ρ the density. This form of the exponent will be justified later on. The explicit dependence of a_λ on the wave length was shown by L. V. King[9] to have the form

$$a_\lambda = \frac{\beta}{\lambda^4} + \gamma$$

where the first term expresses the scattering effect and the second the transformation of light into heat by absorption. The constants β and γ are evaluated in King's paper for some cases and the very general applicability of this formula demonstrated. The same equation can be made to take into account the effect of dust, fog, uneven distribution, and similar conditions by simply multiplying by a factor without changing the form of the equation.

(2) The intensity of the beam.

The illumination of an object is proportional to the candle power of the source, but if there is anything to Weber and Fechner's exponential law between sensation and stimulus the visibility will depend on the initial intensity in quite a different way, and we should expect

$$I = I_i e^{V/V_i}$$

[9] L. V. King. Roy. Soc. Phil. Trans., *212*, pp. 375-433; 1913. Absorption of Light in Gaseous Media. Also: Abstract by the author in Proc. Roy. Soc., Series A, *88*, pp. 83-89; 1913.

where I_t, the threshold intensity, is the smallest intensity visible and V_t its visibility, which can be considered proportional to the probability of seeing the object in question. Solving for V

$$V = V_t \log \frac{I}{I_t}$$

This point could be adequately settled by the psychologist.[10]

If the law holds in this case since I has the form

$$I = \frac{I_0}{r^2} e^{-ar}$$

then

$$V = V_t \left(\log \frac{I_0}{I_t r^2} - ar \right)$$

and V depends on the slowly varying logarithmic function. It may, therefore, very well turn out that variations in initial intensity will prove less important in determining the visibility of an object than meteorological or physical conditions which affect the transmissibility of the air and occur in the expression for visibility in a more direct way.

The relative importance of diffusion of light from the beam as affecting the contrast between beam and target has been pointed out by E. Karrer[11] and by Karrer and Smith.[12]

Still the initial intensity and spectral distribution are the only variables under control and it is essential to pick the best source and to adjust its temperature to the most advantageous value as indicated previously in this paper.

(3) The shape of the beam.

The shape of the beam determines the distribution of intensity on a cross section. How to tell when the proper solid angle and focus are obtained is still an open question. It is desirable to have the intensity spread uniformly over the beam and to have a fairly large area over which objects are illuminated, but both these ends are obtained at the cost of maximum intensity. This, however, according to a previous argument, may not be so important as the gain in time during which the object is visible and the area over which the light

[10] See in this connection H. Lux in papers abstracted in the Physikalische Berichte, 538 and 586, 1921.

[11] E. Karrer. The Effect of Diffusion and Absorption by the Atmosphere on Signal Lights and Projectors. J.O.S.A. & R.S.I., 7, p. 943; 1923.

[12] Loc. cit. footnote 6.

is spread. These matters concerning the physiological properties of the eye should be considered an important part of searchlight investigation. In this connection reference should be made to E. Karrer[13] and especially to G. Gehlhoff and H. Schering,[14] who investigated excessive intensity of illumination, etc.

(4) Luminosity of the beam.

In most respects this is an undesirable phenomenon. It indicates a loss of intensity, due to scattering, shows plainly the position of the searchlight, and worst of all cuts down the contrast between the object sought and the beam itself. Not all of the light scattered in the beam is lost for some finds its way back into the original direction and adds to the direct light. A. Schuster[15] considers this self-illumination an important item in the intensity of the beam. It may contribute as much as ten per cent to the direct light. However, this would be true under conditions when the scattering was extremely large and therefore the distance at which the searchlight would be effective very small both because of the rapid attenuation and the lack of contrast in the very luminous beam.

Since scattered light perpendicular to the beam is polarized at right angles to the original direction, the lack of contrast due to luminosity of the beam itself might be improved by use of analyzing prisms or tourmaline plates, etc. The observer would then have to get off at some distance from the beam and the reflected light from the object might not be very intense in a direction making large angles with the incident beam. Besides, such light would also be polarized and subject to the same elimination in the analyzer as was the scattered light. As a matter of fact this question was taken up from an experimental point of view by Karrer and Smith.[16] They found that under ordinary conditions, (observer within a few hundred feet of the beam and target not too close) the use of a nicol prism does cut down the visibility, and although the data are admittedly incomplete it seems unlikely that polarizers will be of any use in searchlight work.

(5) Meteorological conditions.

The performance of a searchlight depends very largely on weather conditions (fog, mist, rain, wind, etc.). But those conditions under which the searchlight would be of little use would also be very bad for

[13] Loc. cit. footnote 11.

[14] Gehlhoff und Schering. Glare in Relation to Motor Car Headlights. Zeits. f. Tech. Phys., *4*, *9*, pp. 321-333; 1923.

[15] A. Schuster. Radiation Through a Foggy Atmosphere. Astroph. Jour., *121*, p. 1; 1905.

[16] Karrer and Smith. loc. cit. footnote 6, p. 1224.

aircraft so that for anti-aircraft work only fairly clear weather need be considered.

Something in this connection has been done by Karrer and Tyndall[17] who made transmission measurements under various weather conditions, and by A. Mallock[18] who found that the volume fraction of water in the air during a rain is extremely small (10^{-6}), and that the effectiveness of droplets in scattering depends on their distance apart. But besides moisture effects there are other ways in which the condition of the atmosphere may influence the searchlight beam. Most important among these is the dust suspended in the air up to a height of over 1000 m. This dust seems to be ultra microscopic. According to Karrer and Smith[19] the average size of the diffusing particles in a beam with wind blowing more than usual, was about 1.5×10^{-5} cm. Furthermore, an approximate calculation of the rate of fall using Basset's[20] formula shows that particles 10^{-3} cm or greater, and density 2 or more will settle at such a rate that they would not occur in any considerable concentration except possibly under storm conditions. In different localities the height of the dust layer is different and it changes, with wind conditions, volcanic activity, rainfall, etc. Its effect is to absorb and reflect light of all wave lengths out of the beam and to scatter wave lengths greater than 610 $m\mu$. The total attenuation is thus enormously increased in levels up to 1000 m. To take the effect of dust into account, the absorption coefficients must be changed, but the form of dependence on wave length usually remains the same.[21]

$$\alpha=\frac{\beta'}{\lambda^4}+\gamma'$$

Motions of the air have an influence on its transparency in a very mysterious way. O. v. Myrback-Rheinfeld[22] finds that transparency is greatest under anti-cyclonic conditions. He also gives the effect of barometric pressure and surface temperature on transparency.

Another effect of air motion is the opacity due to irregular refractions and reflections, in other words, turbulence. This was pointed out by Rayleigh.[23] A theory of optical opacity of smoke clouds which may be

[17] Karrer and Tyndall. Loc. cit. footnote 5.

[18] A. Mallock. Diffusion of Light by Rain or Fog, Proc. Roy. Soc., *96*, pp. 267-272; 1919.

[19] Loc. cit. footnote 6, p. 1218.

[20] Basset. Hydrodynamics, *2*, p. 271.

[21] See L. V. King. Absorption of Light in Gaseous Media. Phil. Trans. Roy. Soc., *212*, p. 375.

[22] Akad. Wiss. Wien. Sitz. Ber., 119. Mar. 1910.

[23] Rayleigh. Proc. Roy. Soc., 1898, p. 1.

of interest here was worked out by O. F. T. Roberts.[24] This effect may be more important than that due to streaming motion of the air, for it acts both coming and going while the other effects the reflected ray opposite to its effect on the incident beam and almost to the same extent.

(6) The physical conditions of the air.

The optical properties of air seem to depend on its composition and total pressure and apparently on nothing else to any great extent. It used to be assumed that the total mass of gas traversed was sufficient to determine its absorption, but it was found by K. Angström that mere compression or addition of an inactive diluent gas increases the absorbing power. A great deal of work has been done in this connection by Angström and Eva V. Bahr especially, and the results are summarized in the following statements taken from Wood's Physical Optics:

(1) Beer's law $I = I_0 e^{-\alpha m}$ (m is the mass of gas) does not in general hold for gases.

(2) Addition of a foreign gas increases absorption.

(3) Absorption of a mixture is greater than the sum of absorptions of the separate constituents each taken at its partial pressure.

(4) Absorption of a gas mixture is equal to the sum of the absorption of the constituents taken at a pressure equal to the total pressure of the gas.

G. H. Livens[25] deduces the first two statements and says that the fourth is probably not accurately true.

The explanation for this weird effect is probably connected with Einstein's fluctuation theory applied to light scattering. Since the expression is linear in the pressure only for low density we need not be surprised that increasing the total pressure should have more than a proportional effect on the absorption. For low pressures, however, the simple fluctuation theory will hold and statements (3) and (4) will be incorrect. This would escape experimenters because in absorption measurements high pressures are always used, but for meteorological or searchlight theory it will be taken that statements (3) and (4) hold only for gases with partial pressures of a considerable part of an atmosphere.

[24] Roberts. Theoretical Scattering of Smoke in a Turbulent Atmosphere. Proc. Roy. Soc., *104*, pp. 645-654; 1923.

[25] G. H. Livens. Influence of Physical Conditions of a Substance on its Absorption. Phil. Mag., *24*, p. 623; 1912.

Because of the change of pressure and composition of the atmosphere in different places and at different times no general formula can be arrived at for absorption, but account must be taken of the special locality and the conditions then prevailing. How much these conditions affect the transparency of the atmosphere was investigated by O. v. Myrback-Rheinfeld in the paper referred to before. He measured the change in transparency with water vapor, and total pressure. For the effect of water vapor see especially F. E. Fowle[26] who has made a most careful study of the subject. Mention is also made in this work of the effect of dust which even on clear days contributes from 3 to 9 per cent to the absorption of the entire atmosphere above Washington Considering that dust exists only below an altitude of 1000 m, it is evidently much more important in searchlight work than in meteorology where most of the absorption has taken place before the dust has played any part. As for water vapor it turns out that about half the loss in the sun's energy in coming through the atmosphere is due to water vapor. Very detailed accounts of this are given by Fowle including transmission and absorption coefficients for different wave lengths, masses of air, and water content. He also points out that the non-selective absorption is greater than that which would be calculated from laboratory experiments on air with known moisture content.

Since the physical conditions of the air are so important in determining its transmissibility, it is desirable to find how they change during the day. This can be found in meteorological reports and its relation to atmospheric transmission (near midday) is discussed by F. W. Very[27] in his criticism of the work of Abbot. This criticism is answered in the Appendix to vol. 3 of the Annals of the Smithsonian Astrophysical Observatory.

In expressing the absorption of a mixture like the atmosphere, it will be convenient to separate the parts which are independently variable. Thus instead of a single coefficient in

$$I = I_0 e^{-ax}$$

it would be well to have separate terms for (1) the permanent gases, (2) water vapor, (3) dust. It is true that each of these could be separated

[26] F. E. Fowle. Transparency of Aqueous Vapor. Astrophys. Jour. *42*, p. 394; 1915; reprinted with additions in the appendix of vol. *3*, of the Annals of Smith. Astrophys. Obs.

[27] F. W. Very. Atmospheric Transmission. Science *44*, pp. 168-171, 1916.

into a part β/λ^4 due to pure scattering and γ due to absorption, but here where only total attenuation is significant this is unnecessary. The intensity can therefore be written

$$I = I_0 \left(e^{-\rho_g a_g} \cdot e^{-\rho_w a_w} \cdot e^{-\rho_d a_d} \right)^{px}$$

so that the effect of each is expressed as a separate factor. Of course this formula assumes a parallel monochromatic beam, and a homogeneous medium. The changes necessary when these restrictions are removed will be considered later. The coefficients ρ_g, ρ_w, ρ_d give the density of gas, water, and dust. We should really have separate treatment for dust, but it may be worked artificially into this scheme so that a is the absorption of unit mass at unit total pressure. This takes into account the results of Angström and his successors as expressed in the fourth statement quoted from Wood, but the above-mentioned restrictions must be kept in mind.

(7) Effect of Altitude of Object.

In most studies of atmospheric transmission the total absorption for the entire atmosphere is the chief concern and the effect of the different layers is useful only to show how to extrapolate to the space outside the atmosphere from observations at different levels. L. V. King showed that only the total masses and pressure differences between two levels were necessary for the determination of absorption so that the distribution of moisture, dust, pressure, density, and temperature were not of particular interest. On the other hand for anti-aircraft work which deals with altitudes varying up to 3000 meters, it is essential to know just how all these quantities vary with the height above sea level. This question is dealt with in chap. II to chap. IV of Humphrey's Physics of the Air, where data are obtainable for the pressure gradient, temperature gradient, and density gradient, and also some information as to change of composition with height. The work of Abbot[28] also takes this into consideration and refers to Bemporad[29] as taking into account the curvature of the earth, the fall of temperature, and pressure with elevation and atmospheric refraction. He assumes, however, that the optical properties of the air are the same throughout, but owing to the fact that water vapor and dust occur mainly at low altitudes this cannot be taken as approaching the truth. Fowle investigated this somewhat and his work is published in vols. 3 and 4 of the Ann. Smith. Astro. Obs.

[28] Abbot. Ann. Smith. Astro. Obs., *3*, p. 334.

[29] Bemporad. Mitteilungen der grossen Sternwarte zu Heidelberg, *4*, 1904.

It would probably be most convenient to consider the atmosphere as made up of layers homogeneous in themselves, but varying in composition from layer to layer and to give the absorption in each separately. This could be calculated for the different layers under average conditions and a factor applied to take the actual conditions into account. The product of all these quantities up to the height of the object multiplied by the secant of the zenith distance would give the absorption. One application of such a formula would be to calculate over how large areas a searchlight would be effective on a particular night against an object at a given altitude. Of course this depends on the acuteness of vision of the observer, but certainly this should be a known quantity in every case.

(8) The distance of the object.

When it comes to expressing the intensity of a beam as a function of the distance from a point source, we have the formula for homogeneous media to begin with.

$$I=\frac{I_0}{r^2}e^{-\rho a p r}$$

If x is the altitude, then $r=x\sec\zeta$ ($\zeta=$zenith angle) gives a transformation to an easier variable to work with since most quantities are direct functions of the altitude x and are independent of ζ. For a non-homogeneous medium instead of $\rho a p r$ we would use $\sec\zeta\int_0^z \rho a p dx$ and in the case of the atmosphere where $p=p_0e^{-gx/RT}$ and T is a known linear function of x, and when moisture and dust conditions are known, it would be possible to obtain a value for the integral by graphical methods if not by algebraic. But if the air is divided into separate layers and the average of all quantities through the layer taken the formula would become

$$I=\frac{I_0}{r^2}e^{-\sec\zeta a(\rho_1 p_1 x_1+\rho_2 p_2 x_2+\ldots\ldots\rho_f p_f x_f)}$$

where the object is in the f layer and x_i is the thickness of the ith layer, p_i total pressure in the ith layer. When the medium is considered a mixture of constituents (air, water, etc.)

$$I=\frac{I_0}{r^2}e^{-\sec\zeta\sum_j\sum_i \rho_{ji}a_j p_i x_i}$$

when the j's are to be summed over all constituents and the i's over all layers.

When one wishes to find a similar expression for heterogeneous light, a difficulty arises which does not permit a wholly satisfactory solution.

For simplicity consider a parallel beam in a homogeneous medium of unit density and pressure.

$$I = \int I(\lambda)\, d\lambda = \int I_0(\lambda) e^{-a_\lambda x} d\lambda$$

We wish to arrive at a formula $I = I_0 e^{-A(x)}$ where A/x is a total absorption coefficient. Unfortunately A is not a simple linear function of x for

$$I(x) = I_0 e^{-A(x)} = \int I_0(\lambda) e^{-a_\lambda x} d\lambda$$

$$I(2x) = I_0 e^{-A(2x)} = \int I_0(\lambda) e^{-2a_\lambda x} d\lambda$$

$$\therefore \frac{I(2x)}{I(x)} = \frac{e^{-A(2x)}}{e^{-A(x)}} = \frac{\int I_0(\lambda) e^{-2a_\lambda x} d\lambda}{\int I_0(\lambda) e^{-a_\lambda x} d\lambda} \neq e^{-A(x)}$$

unless

$$\frac{da}{d\lambda} = 0$$

and hence in general $A(2x) \neq 2A(x)$.

To express $A(x)$ explicitly take the formula

$$I = I_0 e^{-A(x)}$$

and solve for A

$$A = -\log \frac{I}{I_0} = -\log \frac{\int I_0 e^{-ax} d\lambda}{\int I_0 d\lambda}$$

expand into a Maclaurin series according to the rule,

$$A(x) = A(0) + \frac{x}{\underline{|1}} A'(0) + \frac{x^2}{\underline{|2}} A''(0) + \cdots$$

now

$$A(0) = \log 1 = 0$$

$$-A'(x) = \frac{\int I_0 d\lambda}{\int I_0 e^{-ax} d\lambda} \cdot \frac{\int (-a) I_0 e^{-ax} d\lambda}{\int I_0 d\lambda} \quad \therefore A'(0) = \frac{\int I_0 a\, d\lambda}{\int I_0 d\lambda} < a_{\max}$$

$$-A''(x) = \frac{\int a^2 I_0 e^{-ax} d\lambda}{\int I_0 e^{-ax} d\lambda} - \left(\frac{\int a I_0 e^{-ax} d\lambda}{\int I_0 e^{-ax} d\lambda} \right)^2 \quad \therefore A''(0) = \left(\frac{\int I_0 a\, d\lambda}{\int I_0 d\lambda} \right)^2 - \frac{\int I_0 a^2 d\lambda}{\int I_0 d\lambda}$$

$$\therefore A''(0) < a_{\max}^2$$

and in general

$$A^n(0) < a_{max}^n$$

The series is therefore term for term less than the exponential series

$$e^{a_{max}x} = 1 + \frac{a_{max}x}{\underline{|1}} + \frac{a_{max}^2 x^2}{\underline{|2}} + \cdots$$

and is therefore uniformly convergent, and for moderate values of x (because a_{max} is known to be small), rapidly convergent. It is therefore permissible for moderate values of x or for moderate intervals (say from x_0 to $x_0/3a_{max}$) to use the expression

$$A(x) \doteq x \frac{\int I_0(\lambda) a_\lambda d\lambda}{\int I_0(\lambda) d\lambda}$$

or noting that the coefficient of x is the intensity average of a_λ and calling it $\bar{a}$ we have

$$A(x) \doteq \bar{a}x$$

and

$$I \doteq I_0 e^{-\bar{a}x}$$

or more approximately

$$A(x) \doteq \bar{a}x + \frac{\bar{a}^2 - \overline{a^2}}{2} x^2$$

$$I \doteq I_0 e^{-x\left(\bar{a} + \frac{\bar{a}^2 - \overline{a^2}}{2} x\right)}$$

This calculation is borne out by comparison with the data of Abbot as computed by L. V. King[30] since King uses a formula like the first approximation and finds it to hold accurately from x_0 to $\sqrt{3}x_0$ and then even neglecting the curvature of the earth at zenith distances to 80° it holds to 25 per cent from x_0 to $6x_0$. Abbot remarks that he finds such a formula to be good enough especially when curvature of the earth is taken into account as by Bemporad.

(9) Conclusion.

Taking everything into consideration we may attempt to write down the expression for the visibility of an object in a searchlight beam.

It will depend on physiological characters which will occur as factors; these include the time of illumination, sudden changes in

[30] King. Loc. cit. table 7.

illumination, general illumination of the retina, glare of other lights, acuteness of vision of the observer, all to be included in a function P[31]. Then there is S the sensitivity of the eye as a function of λ. A factor W will take into account the weather conditions such as turbulence, air currents, etc., and L will have to do with luminosity of beam as affecting contrast, so that

$$V(\lambda) = V_i \cdot P \cdot W \cdot S \cdot L \cdot \log \frac{I}{I_i}$$

For I we have

$$I = \frac{I_0}{r^2} R' e^{-\sec\zeta \sum_i \sum_j \rho_{ji} a_j x_i p_i}$$

where R' is a term representing the fact that the light must be reflected from the object and come back to the ground. If R is the reflection coefficient and the observer is near the source, we may write

$$R' = R e^{-\sec\zeta \sum_i \sum_j \rho_{ji} a_j x_i p_i}$$

so that

$$V(\lambda) = V_i \cdot P \cdot W \cdot S \cdot L \left[\log \frac{I_0 R}{I_i r^2} - 2 \sec\zeta \sum_i \sum_j \rho_{ji} a_j x_i p_i \right]$$

For the total visibility according to an argument similar to the one about total absorption coefficient we may substitute average values given by the rule

$$\overline{F} = \frac{\int F(\lambda) I_0(\lambda) d\lambda}{\int I_0(\lambda) d\lambda}$$

and if the visible region is from λ_1 to λ_2

$$V = \overline{V}_i \cdot \overline{P} \cdot \overline{W} \cdot \overline{S} \cdot \overline{L} \left[\frac{\int_{\lambda_1}^{\lambda_2} I_0(\lambda) \log \frac{I_0 R}{I_i r^2} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_0(\lambda) d\lambda} - 2 \sec\zeta \sum_i \sum_j \rho_{ji} \bar{a}_j x_i p_i \right]$$

Now leaving aside $\overline{L}$ and $\overline{W}$ we notice the first term represents the total visibility of the same object under the same conditions except through a non-attenuating medium, therefore we can finally write

$$V = \overline{W} \cdot \overline{L} [V_r^0 - 2 V_i \cdot P \cdot S \cdot \sec\zeta \sum_i \sum_j \rho_{ji} \bar{a}_j x_i p_i]$$

[31] See G. Gehlhoff u. H. Schering. Glare in Relation to Motor Car Headlights. Zeits. f. Tech. Phys., *49*, p. 321; 1923.

The searchlight problem is now clearly subdivided into its independent components. The term V,° has nothing to do with atmospheric transmission. It refers to the character of the light, of the object, of the observer and to the distance. Only the character of light is subject to control and it is the searchlight expert who should find the best distribution and intensity obtainable. For $\overline{V}_t$, $\overline{P}$, $\overline{S}$, and $\overline{L}$ physiological research is necessary and part of it (S) has already been done, although not the low levels of illumination which are important here. It will probably be left to the experimental searchlight operator to determine $\overline{W}$, but possibly a definite anemometric function can be found for it. The meteorologist must give the information about the averages of P_{fi} and p_i and must give means of determining instantaneous values in a convenient manner. As for $\bar{a}_f$ these can mostly be determined pretty well from the data of Abbot, Fowle, and Stephenson, together, —(for accurate values which are probably unnecessary)—with a knowledge of the intensity distribution in the source.

The difficulties in carrying out a complete investigation as outlined may be considerable, but it should be fairly easy to make approximations which will be of very great value in searchlight practice.

The material presented in this report was prepared as part of an investigation on high intensity arcs conducted by Dr. C. B. Stephenson, then of the War Department, in August, 1924. A complete report of this work was made by Dr. Stephenson in an official report to the army; his experimental results were presented to the American Physical Society at Washington in April, 1925, and will be published more in detail probably in this Journal. The author is indebted to Dr. Stephenson for a great deal of his information on the physics of luminous beams and for his kind permission to publish this article. The author also wishes to thank Professor H. Bateman for reading the manuscript and for his suggestions and references.

NORMAN BRIDGE LABORATORY OF PHYSICS,
PASADENA, CALIFORNIA.

Deformation of Single Crystals of Zn, Sn, and Bi.—Experiments on permanent stretch by tension were made accurately at comparatively small tensions, so that whatever change in elastic limit should occur during the deformation could not be ascribed to a change in the orientation of the crystal lattice relatively to the direction of tension. Nevertheless the crystal became very much stronger as it was deformed; in order to keep the deformation proceeding continuously it was necessary to augment the load eventually to 20 times (for a zinc crystal) the value which had sufficed to start it, and a stretch of 0.05 per cent almost doubled the elastic limit. Much the same

result was obtained with Bi, while with Sn the load required to keep the extension going on eventually decreased as the extension increased. The strengthening is more pronounced the more rapidly the load is piled on. From experiments on zinc wires with their axes inclined at various angles to the slip-plane the authors to conclude that the plastic deformation of a hitherto unstretched wire commences when the shearing stress in this plane amounts to a critical value of about 36 g/mm², irrespective of the direction of the tension. After a crystal is deformed and then left to rest for a few minutes or even seconds, it can be further deformed by a lesser load than originally just sufficed to deform it thus far and no further. This phenomenon was investigated and measured upon Sn and Bi crystals, using as measure of the "recovery" the rate of flow of the crystal under long-continued steady application of the load. Upon zinc it was studied by direct measurement of the load required to increase a 50 per cent elongation, at various time-intervals after the elongation had been effected; after a few hours this was hardly greater than the load initially required to start deformation of the unstretched crystal.—[O. Haase and E. Schmid, Kaiser-Wilhelm Institute; ZS. f. Phys., *33*, 413-429; 1925].

KARL K. DARROW

X-ray Scattering by Molecules with Equal Numbers but Different Arrangements of Electrons.—Bragg has emphasized that in such cases as occur in a RbBr crystal, where the Rb atoms have lost and the Br atoms have each gained an electron so that every atom is a group of 36 electrons, all the atoms have the same scattering power; as is evinced by the vanishing of diffraction-lines of certain orders. In such cases however there is reason to believe that not only the number but the arrangement of the atoms is the same for all atoms; if the first of these things were true and not the second, would the result be the same? Anhydrous $SrCl_2$ is a salt in which x-ray crystal analysis shows that the Sr atoms and the Cl_2 molecules form two interpenetrating lattices, as in the more familiar case of CaF_2; the Sr atom and the Cl_2 molecule should each have 36 electrons, but since one is a system with one and the other a system with two nuclei there is every reason to believe that the 36 electrons will not be arranged in the same way in the two. The x-ray analysis in fact shows that the lines which should vanish, were the scattering powers of atoms of the two kinds identical, are quite perceptible. Another interesting test is made upon RbBr itself using radiation which is absorbed much more strongly by the Br atom than by the Rb atom. The radiation used is the K α-radiation of Sr, which is of high enough frequency to eject K-electrons from Br but not from Rb atoms. Observations on the diffraction lines show that this difference sufficesto destroy the even balance between the scatterings effected by the Rb and the Br ions.—[H. Mark and S. Tolksdorf, ZS. f. Phys., *33*, pp. 681-687; 1925; H. Mark and L. Szilard; ibid. pp. 688-691.]

KARL K. DARROW

A GENERAL UTILITY READING-LENS FOR BURETTES AND THERMOMETERS

By Elliot Q. Adams

ABSTRACT

A reading-lens for burettes and thermometers is described in which errors due to parallax are eliminated by an ocular slit at a distance in front of the lens equal to its focal distance. Spring clips above and below the lens tube give a high degree of rigidity combined with applicability to a wide range of burette or thermometer diameter. For reading the lowest point of the meniscus in burettes filled with a colorless liquid, a spring of sheet brass holds against the back of the burette a suitable ruled background. Two types of background are described, giving either maximum ease and precision of reading, or else, by obviating the necessity for an accurate placing of the reading lens, speed.

A reading device for burettes or thermometers can increase the ease and accuracy of reading in three ways: by magnifying the scale divisions, by avoiding the error and particularly the uncertainty due to parallax, and by reducing the annoyance caused by the difference in focus of the scale and the thermometer thread or burette meniscus. In the case of a burette with a colorless liquid, it may also furnish a suitable and suitably placed background for viewing the meniscus.

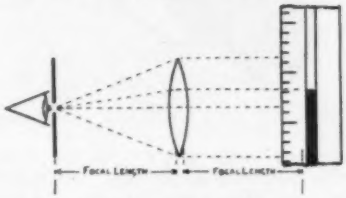

Fig. 1. *Diagram of optical system.*

The commercially available burette-readers furnish adequate magnification, but avoid parallax only if the point of reading falls at a fixed place in the field, indicated in some instruments by a pointer. It is, however, possible to eliminate parallax (within the aberrations of the lens used) over the entire field, by fixing an ocular slit in front of the lens at a distance equal to its focal length, as may be seen from Fig. 1.

Since horizontal parallax is not to be feared, a slit minimizes the vertical parallax with much less sacrifice of light than would result with a circular aperture. A slit also gives better definition of *horizontal* lines not in the focal plane. With a lens of 3.5 cm focal length and 1.3 cm aperture, a slit 0.15 cm wide gives satisfactory results. This aperture

corresponds to a field of 7 to 10 scale divisions on most burettes or thermometers.

To take full advantage of this width of field, the supporting clamps must not obstruct the view. The writer is indebted to Mr. George Hathaway of the Nela Research Laboratory machine shop for designing and constructing the clamps shown in Fig. 2. This type of clamp gives a surprising degree of rigidity, combined with ability to hold securely on a small thermometer stem or a large burette, but can be used only when it is possible to slip the clamps onto one end of the thermometer or burette.

Readings on a burette filled with a colorless liquid require either a float bearing a horizontal line, or a suitable background for making visible the lowermost point of the meniscus. Such a background is held against the back of the burette by a spring of sheet brass soldered to

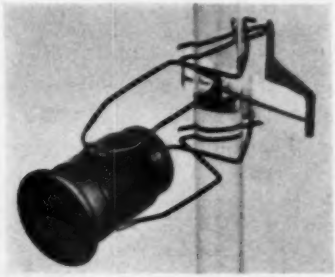

FIG. 2. *Device attached to burette filled with colorless liquid.*

two free ends of the supporting clamps. This construction has the incidental advantage of making the attachment move smoothly along the burette, by constraining the two clamps to move simultaneously.

When ease and precision of reading are most important, a very satisfactory background consists of a single horizontal black (or red) stripe, 1.5 mm wide, on a white field. This line is placed with its upper edge below and nearly tangent to the bottom of the meniscus. This type of background sacrifices one of the advantages of the reading-lens, namely the possibility of reading at any part of the field of view. A background of alternate black (or red) and white horizontal stripes, each 0.5 mm wide, gives a field which permits readings at any point in the field of view. By obviating the necessity for accurate placing of the reading lens, the speed of reading should be increased. (Better still, a Schellbach (blue-stripe) burette may be used.)

While the clamps shown will bring the center of the thermometer or burette to a fixed distance from their point of attachment, the difference in indices of air, water, and glass causes a variation in the location of the virtual image of the mercury thread or meniscus. (See Fig. 1.) To permit adjustment for this, and for uncorrected errors of refraction of the observer's eye, the slit and lens are mounted, the proper distance apart, in a tube which slides in the tube to which the clamps are attached.

The over-all length of the device, as shown in Fig. 2, is less than 10 cm, and its weight less than 50 g.

NELA RESEARCH LABORATORY,
CLEVELAND, OHIO.
SEPTEMBER, 1925.

Behavior of Optically-Active Crystals Illustrated by Space-lattices of Hertzian Resonators.—Lindman constructed eighty tetrahedral "molecules" out of brass spheres 18 mm in diameter arranged in fours at corners of a cube 28 mm on a side; their positions may be described by saying that if the coordinates of one sphere of a tetrahedron be represented by (0,0,0) those of the others may be represented respectively by (28,0,0), (28,28,0) and (0,0,28). The tetrahedra are thus not regular. Each "molecule" was embedded in a ball of paraffin, and the eighty balls were packed into a box, presumably with an effort to avoid all tendencies toward systematic orientation. Waves of wave length 17.6 cm, or 22 cm, or 26 cm, (the natural frequency of the "molecule" amounting to a wave length 10 cm) were generated by a Hertzian resonator and sent through the lattice of spheres to a receiver, of which the azimuth (in the plane normal to the line of propagation of the waves) could be varied at will. In the absence of the "molecules" the curve of receiver-reading-vs-azimuth had a (smoothly rounded) maximum at the azimuth for which receiver and oscillator were parallel; when the balls were packed into the path of the waves, the maximum moved clockwise through about 4°. It must be admitted that, if the reproduced figures are typical, Lindman made readings at too few azimuths to be able to trace a truly reliable curve; yet his estimates of the azimuth for maximum receiver-reading are quite concordant. It is particularly noteworthy that the sense, as well as the amount, in which the plane of polarization was rotated remained the same when the box containing the "molecules" was revolved or even turned completely around in the path of the rays. The dependence of the effect on wave length conformed well to the familiar formula $c/(\lambda^2-\lambda_0^2)$; but, of course, measurements at three wave lengths only do not mean much. Similar results had previously been obtained by Lindman with a single such "molecule" built of larger spheres, although the orientation of the model relatively to the rays naturally influenced the effect; with a set of nine spheres arranged

along a spiral curve, which produced a rotation changing in sign when the wave length of the waves passed across that of the natural oscillations of the spheres, and likewise with lattices made of spiral pieces of metal. The net result is, that an interesting realization of three of the models (Drude's spiral electron-paths, Oseen's irregular-tetrahedron molecules, and Bragg's spiral arrangements of atoms) proposed to interpret optically active crystals has been achieved.—[K. F. Lindman, Abo: Ann. d. Phys., *77*, pp. 331-357; 1925].

KARL K. DARROW

Interval of the Kα-Doublets of Light Elements.—The interval between the components of the *K*α doublet is interesting because values were calculated for it by Sommerfeld from the assumption that the components result from transitions of an innermost electron into a 1-quantum circular orbit from 2-quantum circular and elliptical orbits respectively, and these have agreed well with experimental values for massive elements. Values obtained by Bäcklin for the elements from 13 to 20 inclusive (excepting 18, which is argon) lie neatly upon a smooth curve prolonging the curve for massive elements. This result is in contradiction with earlier experimental ones, which may arise from the difficulty of estimating visually the true maxima of two diffuse overlapping lines; for the *K*α lines become very broad and vague as the atomic number sinks. When any of these atoms is in chemical combination, the *K*α doublet is displaced markedly towards higher frequencies. Some excellent photographs show how the *K*α doublet of sulphur is displaced, by combining the sulphur into a sulphate, just sufficiently to bring the α_2 line where the α_1 line was before; so that a mixture of sulphur and sulphate, as one gets when sulphur is spread over an Al plate and bombarded long enough, displays an apparent perfect triplet of equally-spaced lines.—[E. Bäcklin, Upsala; ZS. f. Phys., *33*, pp. 547-556; 1920.]

KARL K. DARROW

Continuous Spectrum of Hydrogen.—The continuous emission-band of hydrogen which extends from shorter wave lengths up to about 4800A is found to vary in intensity, when the circumstances of excitation are varied, otherwise than as the Balmer lines and the many-lined spectrum vary; in particular it is favored by electric field-strength (which is altered, *ceteris paribus*, by altering the size of the cathode of a glow-discharge) and by mixing the hydrogen with calcium vapor. The authors think that it results from recombination of atoms into molecules, a process which is possibly inhibited in the absence of electric field; while the Ca atoms may be conceived to promote it by promoting the inverse effect (dissociation).—[H. Schüler and K. L. Wolf; Potsdam; ZS. f. Phys., *33*, pp. 42-47; 1925.]

KARL K. DARROW

A NEW MULTIPLE X-RAY SPECTROGRAPH COMBINING THE POWDER DIFFRACTION AND MONOCHROMATIC PINHOLE METHODS

By George L. Clark, Elmer W. Brugmann, and Robert H. Aborn

For the past two years one of the writers has been conducting research with the object of bringing the science of x-rays, particularly the determination of ultimate crystal structures, to bear upon the problems of manufacture and the properties of technical materials. This has involved the development of an apparatus, suited for use in scientific and industrial laboratories, with which these investigations can be made rapidly and economically.

Provision is made in the apparatus for use of the monochromatic pinhole and powder diffraction methods. Neither method alone is adequate and both must ordinarily be used to obtain full and quantitative information about a specimen.[1]

MONOCHROMATIC PINHOLE METHOD

The great value of this method is only now becoming recognized, although in bringing it to bear upon practical problems of industry for the first time, the writers have been perfecting it for two years.

The orientation of crystal grains with respect to each other and the condition of strain within the grains are readily ascertained. The spectrograms show the effect of rolling or drawing in producing preferred crystal orientation and directional properties, and the extent to which annealing and heat treatment overcome these effects. The differences made by hot and cold rolling in steel products and in all metals and alloys are readily followed. The study of regions of strain in cast metal with their removal by heat treatment and the resultant standardization in foundry practice is very promising. Information gained by the monochromic pinhole method concerning grain size, lattice type, and lattice dimensions is most important in regard to quenching, annealing, tempering and the magnetic properties of metals, as well as in regard to the state of combination, crystallinity, and purity of all solids. Electrolytic deposits produce pinhole diagrams which

[1] A precision equipment including a Société Genevoise Instruments d'Physique ionization and photographic spectrometer installed in the writers' laboratory, is described in Industrial and Engineering Chemistry, *17*, p. 1147, Nov. 1925.

prove that they have definitely oriented grains with the fiber axi perpendicular to the electrode surface.

Typical diagrams of steel are reproduced in Figs. 1, 2 and 3. Th first shows the fiber structure of a cast steel bar which has been fractured by pulling; the second, the diagram of an annealed commercial shee steel in which residual orientation is still apparent; and the third, an annealed specimen in which large grain size and absence of strain are desirable. Numerous other typical diagrams for commercial metals are reproduced in another paper.[2]

The monochromatic pinhole method is not limited to the study of metals, for preferred orientation in waxes and organic substances as well as the development of fiber axes in cellulose, balata, and rubber yield to it. The great advantage of the method is that no special

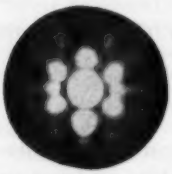

FIG. 1. *Monochromatic pinhole diagram showing fiber structure in a cast steel bar fractured by pulling. Fiber axis, [110] direction, vertical.*

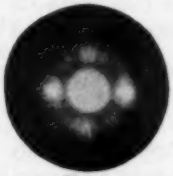

FIG. 2. *Typical diagram for commercial low carbon sheet steel, showing residual grain orientation after annealing.*

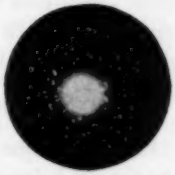

FIG. 3. *Diagram of annealed silicon steel in which large grains and absence of strain or orientation are desirable.*

preparation, polishing or pulverization of the specimen is required. The x-ray beam passes through or is reflected from the surface of the material, so that the result is exact information upon the material as it is practically used.

When the specimen consists of small crystals (200 mesh) randomly oriented, either as a loose powder or united as in some metals, the pattern consists of a series of concentric circles, the center of which is the trace of the main beam. The relation between the spacing of these concentric circles and the lattice type and dimension is the particular province of the powder diffraction method.

[2] Clark, Brugmann, and Heath, "New X-Ray Studies of the Ultimate Structures of Commercial Metals," Ind. & Eng. Chem., *19*, p. 1142, Nov. 1925.

POWDER DIFFRACTION METHOD

The powder diffraction method tells the crystallinity, purity, and particularly well, the crystal lattice type and dimensions, since the spacings of line spectrum may be very accurately measured.[3]

Since the specimen must consist of small crystals for satisfactory results, the method gives some idea of crystal size. The use of this method and excellent commercial apparatus, many features of which we have incorporated in the present apparatus, are described elsewhere.[4]

APPARATUS

Eighteen exposures can be taken simultaneously through apertures arranged radially around a self-rectifying molybdenum Coolidge tube whose axis is vertical. Each aperture will receive either a double pinhole or a double wide or restricted slit. When a pinhole is used the pattern is recorded on a ($3\frac{1}{4}\times4$ or 5×7 inches) flat film held perpendicular to the x-ray beam. When a slit is used the pattern is recorded on a strip of film $1\frac{7}{8}\times16$ inches held on a semicircle with the specimen at the center. Using a circular cassette at alternate apertures, the flat cassettes are shielded from stray radiation and nine pictures of each type are taken simultaneously. The Coolidge tube is excited by a transformer enclosed in the base of the apparatus. The positive terminals, the transformer case and the entire exterior part of the apparatus are connected to earth. Exclusive of the control panel, the over-all dimensions are 32 inches in diameter by 55 inches in height. A photograph of the apparatus is reproduced in Fig. 4.

APERTURE SYSTEM

The eighteen apertures are equally spaced around the circumference of a cylindrical steel head 18 inches in diameter. In each opening a brass tube in a collar, so arranged that it can be adjusted 1/16 inch vertically or horizontally, focuses on the target and makes an angle of five degrees with the target face. Either a double pinhole (of different sizes depending upon the nature of the material to be investigated) or slit can then be quickly focused by slipping into the tube. Each tube can be adjusted, independently of the others, to the focal spot on the target and then fixed permanently by tightening the screws in the collar. Openings not in use are covered with $\frac{1}{8}$ inch lead caps.

[3] A Brown and Sharpe vernier-caliper with a fine tungsten wire as hair line attached to one jaw is proving most satisfactory in this laboratory.

[4] "A New X-Ray Diffraction Apparatus." W. P. Davey, J.O.S.A., *5*, p. 6, Nov. 1921.

Double pinholes should always be used because a single pinhole gives an image of the focal spot or of the target superimposed on the crystal pattern. With the pinholes separated four inches, a pinhole diameter of 0.06 inch enables quick exposure and sufficient detail for ordinary work. A ZrO_2 filter (0.025 gm/cm²) can be placed in a small recess over the pinhole nearer the target.

CASSETTE TABLE

The aperture head is located by a dowel pin in a hole in a ⅜ inch steel plate whose diameter is 32 inches. Corresponding to each aperture in the head, there is a T-slot guide for the cassettes on this plate.

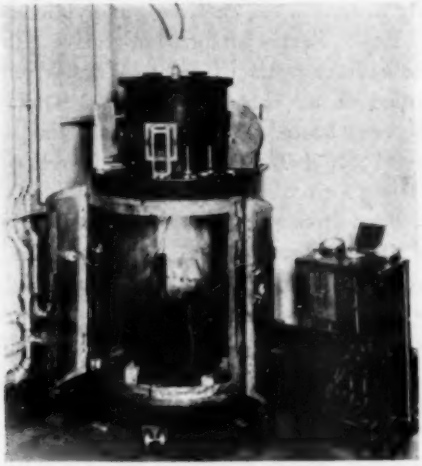

FIG. 4. *Photograph of new apparatus, showing pinhole and slit system, 2 types of cassettes, transformer and control stand.*

TUBE MOUNTING

The regular self-rectifying molybdenum Coolidge x-ray tube is mounted on the axis of the head and is held at the earthed anode end by a set screw which permits vertical adjustment. The cathode end hangs freely excepting for a short electrical connection to the high tension transformer bushing. Once the correct adjustment of the target is made, the opening around the anode is closed with sealing wax to prevent cracking the tube by water which condenses on the cooling water leads. Cooling water is supplied to the grounded anode by iron pipe and fabric rubber hose. A "mercoid" switch in the water line

is adjusted to stop the x-ray machine by a relay when the water pressure falls below 25 lbs./square inch. The tube which is designed to carry thirty milli-amperes at 30 kv_{RMS} and operates on a space charge characteristic, is very satisfactory for crystal analysis.

PINHOLE CASSETTES

Flat cassettes in which calcium tungstate intensifying screens are mounted are used to record the pinhole patterns. For ordinary use films $3\frac{1}{4}\times 4$ inches suffice, although the size 5×7 inches can be used for special work. Each cassette is labelled in bold $\frac{3}{4}$ inch numbers with radium paint in order that it can be identified in the dark room.

The cassettes are automatically held perpendicular to the x-ray beam during exposure by means of easels which can be locked in the T-slot guides at any desired sample-to-plate distance up to 6 inches. In the back of each cassette are two pins which fit into slots in the top of the easel and permit quick adjustment or removal of the cassette. Cassettes of two sizes with their easel mountings are clearly shown in Fig. 4.

POWDER CASSETTES

The film ($1\frac{7}{8}\times 16$ inches) is automatically held on a semicircle of twelve centimeter radius at whose center the specimen is fixed. The use of a semicricle, rather than a quadrant, for powder work permits measurement of the pattern without reference to the trace of the zero beam. The zero beam passes through the sample and on a brass stop-piece, enclosed by a sheet brass baffle to prevent secondary radiation from reaching the film. Sheet aluminum (0.012 inch thick) is used on the sample side of the film to filter out light rays and to pass the x-rays. When the accuracy required permits, intensifying screens can be mounted on both sides of the film to reduce exposure time. Zirconium oxide filters are mounted in the cassette and also over the slit nearer the tube. They filter out most of the general radiation and the Mo$K\beta$ and $K\gamma$ rays, thus giving a diffraction pattern due to the $K\alpha$ doublet alone.

A septum divides the cassette so that a standard pattern from a substance such as NaCl can be recorded directly on the film with the unknown pattern. One of these cassettes is shown adjusted on the right of the top of the apparatus in Fig. 4.

SAMPLES AND MOUNTING

Metal samples for use with the pinhole method should be thin in order to reduce the time of exposure. About one to two hundredth inch is satisfactory in the case of iron, although much thicker samples can be used. Samples are roughly cut out with a hack saw or milling cutter and are slowly and uniformly ground on an automatic lapping machine. Great care should be taken to preserve the original structure and to avoid cold working or overheating of the sample. The sample is then etched to remove the surface layer of cold worked material, washed in alcohol, dried, and finally lacquered to prevent corrosion.

Samples of this sort are mounted directly on the pinhole nearest the cassette. Plasticine is satisfactory for holding the sample. It is not necessary to completely cover the pinhole with the sample, although this is usually done. In cases where the part to be studied is the surface, the beam can be made to impinge on it at definite angles and the picture obtained by reflection. This procedure is necessary many times, notably in the study of electrolytic metal deposits which have their fiber axes perpendicular to the large electrode surface. A photograph taken with the beam passing through such a sheet (and hence parallel to the fiber axis) gives no evidence of any oriented structure. Hence it is necessary for the angle of incidence to be changed.[5] Provision is also made to rotate the entire pinhole with the specimen attached in order to convert fiber diagrams with isolated maxima into rings for more careful identification.

Powders ground to 200 mesh, for use with the powder diffraction method, are contained in fine capillary tubes or suspended in collodion from which a thin film is then prepared. This film is mounted on the cassette and a restricted slit 0.01 – 0.05 inch wide is used to define the x-ray beam and to determine the line width on the pattern. Other methods for using the powder diffraction method have been mentioned.[3]

EXPOSURE

Using $CaWO_4$ intensifying screens satisfactory pinhole exposures can be made through a two-hundredth inch sample of steel in 50-150 milliampere hours. The sample-plate distance is 5 cm., the pinhole separation 4 inches, and pinhole diameter for general purposes 0.06 inch.

The exposure time is integrated by means of a synchronous electric clock connected on the control panel to operate only when the tube is excited.

[5] Clark and Frölich. ZS. Elektrochem., *31*, (p. 655); 1925.

PROTECTION

The ⅜-inch steel head is lined with ⅛-inch sheet lead to protect the operator and films from the x-radiation. Similar protection is provided on the lid from which the tube is suspended. The base enclosing the transformer is made of $\frac{1}{16}$-inch galvanized iron lined with $\frac{1}{16}$-inch sheet lead. No additional protection is used to prevent radiation from penetrating through the ⅜-inch steel table top, because it is not directly exposed.

VENTILATION

Air to cool the tube is drawn by a fan through an air cleaner to remove dust and is first directed to cool the transformer. It then passes by the tube and leaves through the vents on the top plate.

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Photoelectric Current elicited from Pt, Au, Ag by black Radiation.—This is determined by Suhrmann not by direct use of black radiation, but by measuring the photoelectric current produced by illuminating foils of these metals 0.01 mm thick with monochromatic light of numerous wave lengths between 2250 and 3650A. The intensity of the light is measured with a thermopile, and allowance made for the reflection by the metal, so that the data yield the photocurrent per unit absorbed energy as function of frequency; this function is then multiplied by the Planck radiation formula and integrated to obtain the desired total current which black radiation would produce. Rather unexpectedly it is found that in spite of the rapid increase of photosensitiveness with rising frequency, the integral photocurrent produced by black radiation as hot as 2000°K would be due almost entirely to the wave lengths exceeding 2250A, and the maximum effect would occur at a wave length greater than 2500A. The integral current i, when plotted versus the temperature T of the black radiation in the manner familiar in thermionics, is seen to conform to the equation

$$i = MT^2 \exp(-n/T)$$

in which M and n stand for constants. [As in thermionics, however, it seems likely that equally good agreement could be attained with almost any other factor in place of MT^2.] Suhrmann compares n with the photoelectric work function as deduced from the threshold wave length which he observes; it always comes out a little greater. He thinks that n gives the true value of the work function, and that the threshold wave length is altered by the fact that electrons which absorb from the light not quite enough energy to emerge through the surface may acquire the rest from the thermal agitation of the atoms—an idea which could be tested. Incidentally, it appears that a brief glowing of

the foil of any of these metals raises its photo-sensitiveness vs. frequency curve tremendously, presumably because a retarding gas film is driven off; while a larger glowing reduces that of Pt and (to a less extent) that of Au, but not that of Ag. Since the first two metals occlude H_2, silver O_2 but not H_2, Suhrmann reaches the interesting conclusion that occluded H_2 promotes the photoeffect but occluded O_2 does not. It is suggested that the equation cited above for i is accurate enough to make the photoelectric cell usable as a pyrometer for black radiation. [R. Suhrmann, Breslau; ZS. f. Phys., *33*, pp. 63-84; 1925.]

KARL K. DARROW

Excitation of the Spectrum of Atomic Nitrogen.—These researches have several features of unusual interest. In the first place, Merton and Pilley have apparently made the first mapping but one of the spectrum of neutral atoms of nitrogen—atoms which are evidently very difficult to isolate, especially as it now seems established (by measurement of the heat of dissociation) that it requires 19 equivalent volts to dissociate an N_2 molecule into two neutral N atoms. They obtained the spectrum by condensed discharges through a tube containing helium at the high pressure of 30 mm and a very minute admixture of nitrogen; otherwise the molecular spectrum of N_2 and the spark spectrum of N are the only ones visible. Excessive care had to be taken to avoid all contamination, and some interesting advice on this matter is given. When argon was substituted for the helium, it was impossible to find any of the lines of the spectrum of neutral atoms. This influence peculiar to helium could be explained in a general way by saying that helium is the only gas in which electrons can make any number of collisions without being prevented thereby from attaining an energy of nearly 21 equivalent volts, and that the nitrogen must be scanty so that recombination of detached atoms will not be immediate. K. T. Compton, however, considers that the dissociations are effected not by electrons but by excited helium atoms in collisions of the "second kind," the excited helium atom returning to its normal state and transferring the energy so liberated to the molecule. Since there are both electrons and excited helium atoms in the discharge tube, it would probably be impossible to distinguish by these experiments between these two ideas. But as Compton says, attempts to produce the atomic spectrum by bombardment of pure nitrogen with 20-equivalent-volt electrons have failed; and other test-experiments might be devised. A particular spectrum of carbon is also brought out in the presence of a vast excess of helium, though not of argon, as Johnson and Cameron have shown. [T. R. Merton and J. G. Pilley, Oxford; Proc. Roy. Soc., *A 107*, pp. 411-422; 1925. K. T. Compton, Princeton; Phil. Mag., *50*, pp. 512-516; 1925.]

KARL K. DARROW

THE OPTICAL STUDY OF PERCUSSION FIGURES

By C. V. Raman

ABSTRACT

The application of optical interference methods to the study of the small local deformations occurring in impact is indicated as likely to lead to an extension of our knowledge of such deformations. As an illustration of the usefulness of the method, interference photographs showing the surface deformations produced by the percussion of a polished steel ball on a thick glass plate are reproduced. The photographs show the percussion figure to consist of three distinct regions.

a. A central area which remains plane and practically undisturbed except for a small permanent lowering of its level.

b. A narrow annular region of fracture showing severe injury to the surface.

c. A sudden elevation of the surrounding surface which slopes down gradually to the general level of the plate at the outer margin of the area of internal fracture.

As is well-known, a theory of the elastic deformations produced when two solid bodies with curved surfaces are pressed into contact was developed by Hertz,[1] and applied by him to a consideration of the phenomena occurring during the impact of such bodies. The theory takes no account of the *irreversible* deformations such as actually occur in practice under sufficient static pressure or in elastic collision, and of the consequent dissipation of energy; it does not therefore completely describe the phenomena. Nevertheless the theory serves as a first approximation and is a useful guide in attempting to understand the behavior of imperfectly elastic materials in hardness or impact tests. In special cases, as for instance when the impact velocities are very low,[2] or when no energy loss occurs except that due to production of vibrations in the impinging bodies,[3] Hertz's theory fits the facts tolerably well or at any rate can be suitably modified. It is more difficult adequately to take into account the effect of inelastic deformations on the course of the phenomena of impact, particularly because the element of time enters in the problem in a somewhat complicated way. Nevertheless it may be hoped that an exact experimental knowledge of the subject may pave the way for further developments in theory.

It occurred to the writer that an application of optical interference methods might be useful in extending and making more precise the

[1] Hertz, Miscellaneous papers, English Translation, p. 146.

[2] C. V. Raman, Physical Review, 2nd Series, *12*, p. 442, 1918.

[3] C. V. Raman, Physical Review, 2nd Series, *15*, p. 277, 1920. See also, J. Okubo, Tohoku Univ. Sc. Reports, *11*, pp. 445-461, Dec. 1922.

knowledge of the local deformations occurring in impact. The interference lines between the deformed surface and an optical flat would form an accurate contour map which could easily be measured up and interpreted, and the sensitivity of the method would be such that deformations as small as 10^{-5} of a centimeter could be accurately determined. In the case of metallic surfaces, a difficulty which presents itself is that the reflecting power of a polished metallic surface is usually much higher than that of an optical flat of glass or fused quartz, and the visibility of the fringes between them is therefore somewhat low. This may however be overcome by half-silvering the lower face of the optical flat and thus making the reflecting power of the two boundaries of the air film nearly equal. Work on these lines has been undertaken by Mr. Kedareswar Banerjee, a research student under the writer's direction, and the results obtained will be reported in due course. As an indication of the usefulness of the method suggested in the study of the deformations produced by elastic impact, the writer wishes to present three interference photographs obtained by him showing the effect of the collision of a polished steel ball 2 cm diameter on the surface of a thick glass plate. The percussion figure obtained in this case was described by the writer some five years ago in a communication to Nature.[4] Its remarkable character is brought out in a striking way when an optical flat is laid on the deformed surface, and the interference fringes between the contiguous faces are observed in monochromatic light. Figs. 1, 2 and 3 are photographs obtained in this way, (magnification about five diameters), a quartz mercury lamp with quinine sulphate filter being the source of light used. In Fig. 1, the two surfaces were nearly parallel, in Fig. 2, somewhat more inclined to each other and in Fig. 3 further inclined still.

An inspection of the photographs shows three distinct regions in the percussion figures. Firstly, there is a central area, nearly circular which, apparently, is unaffected by the impact as is shown by the fringes passing through it in Fig. 3 being straight and parallel. Secondly, there is a narrow annular region of fracture full of a net-work of irregular fringes, showing severe injury to the surface. Thirdly, and just beyond this, there is a sudden elevation of the surface, of about four wave lengths, which slopes down first quickly, and then more slowly, to the original level of the surface at the edge of an area which sets the limit to the percussion figure. Closer examination reveals another remarkable

[4] C.V. Raman, "Nature," Oct. 9, 1919.

feature, namely, that the central area of the percussion figure, though it remains plane and apparently undisturbed has, in reality, been *depressed below* the original level of the surface by an appreciable fraction of a

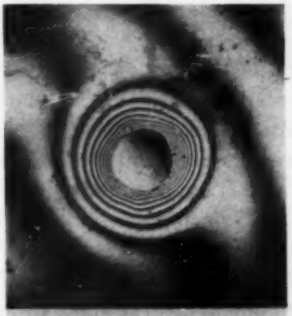

FIG. 1. *Percussion Figure: Interference pattern with test-plate nearly parallel to surface of glass block.*

FIG. 2. *As in Fig. 1, but with the test-plate not parallel to surface.*

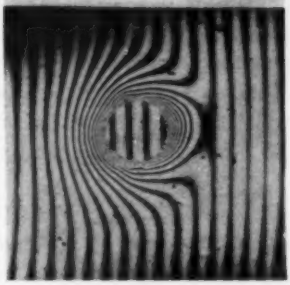

FIG. 3. *As in Fig. 2, but with still larger tilt of test-plate.*

wave length, as shown by the fact that the course of the fringes outside the percussion area and within the central circle are distinctly out of register. This feature will be evident on a scrutiny of all three photo-

graphs and has been found to be an invariable feature of the percussion figures produced even on very thick glass plates by the impact of steel balls.

An explanation of these features on Hertz's theory of impact may be ventured, though some points still remain obscure. The nature of the stress distribution in the case of a sphere resting on a plane has been worked out by S. Fuchs[5] who has given a diagram of the lines of principal stress. Near the central compressed area both the principal stresses are pressures, and the glass stands the compression without giving way. There is a narrow annular region surrounding the central area where one set of principal stresses are pressures and the other set are tensions. The shearing stresses are a maximum in this region and the glass gives away, the circular crack spreading obliquely inwards into it for a considerable region. When the crack forms, the surface of the glass on its outer side is raised up and dips down slowly to the edge of the area covered by the extension of the internal fracture-surface. The small permanent depression of the central area remains, however, a mystery. It does not seem possible that it can be due to any actual flow of the glass during the impact, as the time available is all too short for such flow to occur, and as, moreover, there is no sign of the area in contact with the sphere acquiring any appreciable curvature, as could reasonably be expected if viscous flow occurred. Accepting the reality of the phenomenon, the only explanation of it that the writer can offer is that, at the instant the crack starts and spreads inwards, part of the material which has shifted its position outwards under the intense compressive forces remains outside it and is unable to return. The level of the central area is thus permanently lowered when the stress is removed. Further studies of the phenomenon under large static stresses would be of interest.

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[5] S. Fuchs, Physikalische Zeitschrift, p. 1282, 1913.

CAPILLARY VALVES FOR GASES

By J. J. Hopfield

It is often convenient in studying gases spectroscopically to allow them to flow through the discharge tube and thus to insure their purity. Also it is sometimes desirable to mix flowing gases in any given proportion in the vacuum tube.

In order to permit such a flow of gas, long capillary tubes of glass are generally used. Of course such a capillary can give only a constant gas flow. The two capillary valves described herein are designed to permit a variable flow of gas. They are shown diagrammatically in Figs. 1 and 2.

Fig. 1 shows the more complex type. The diagram is drawn approximately to scale in the vertical dimension. In this figure *A* shows an iron core enclosed in glass which is fused to the glass needle *C*. A solenoid *B* pulls this needle in and out of a glass capillary *D*. *E* is a glass tube used to protect the capillary. The needle and the capillary are

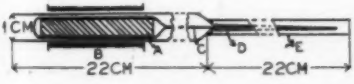

Fig. 1

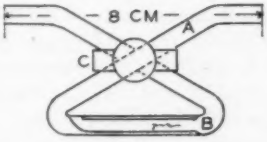

Fig. 2

really much finer than could be adequately drawn in the picture. The glass needle works better when it is made of soda-glass. The rest of the instrument can be made of either soda glass or pyrex. A typical valve will give as small gas flow as 0.1 cc (measured at atmospheric pressure) per hour when the gas passes from atmospheric pressure into a vacuum. By moving the needle this flow can be increased about 250 fold. The valves can be manufactured either coarser or finer than the one described. They can be calibrated also.

The second capillary valve is shown in Fig. 2. The sketch representing it is drawn to scale. This instrument is made of two small pieces of glass tube and a metal pinchcock. *A* shows the outer glass tube and *B* the inner one. This latter contains a lengthwise crack (see figure) and a transverse crack branching from it. *C* is a pinchcock. Pyrex glass is recommended for the construction of this valve. The inner tube is

fused to the outer one as represented in the diagram. In operation the left end of A is connected with the vacuum. The principle of its action is as follows: The two arms of the outer tube are slightly separated and the pinchcock when operated decreases the separation thus producing a slight twist in the tubes. This twist in turn opens the crack in the inner tube. The valve can be easily made to give as wide range of variation as the first one described. It is not easily broken by springing the arms together for it is made so that the arms come in contact before the elastic limit of the glass is reached. This precaution also allows one to calibrate the valve satisfactorily. In fact this valve has all the good features of the first and besides it is much more simple and compact.

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Alterations of the X-ray Spectrum of Sulphur Atoms caused by Altering their Chemical State.—Measurements on the $K\alpha_1$ and $K\alpha_2$ emission lines of sulphur in the elementary state, in many sulphides in which it appears as divalent, and in many sulphites and sulphates in which it appears as quadrivalent show that their wave lengths are quite accurately 5360.90 and 5363.90 respectively, for elementary sulphur (rhombic and "plastic" both) and for all sulphides; while for all sulphites and sulphates they are displaced to 5358.50 and 5360.90 respectively. As the variation in the K extraction-potential has been previously measured as 0.5%, these data show that the L extraction-potential is changed (increased) by about 9%—a considerable difference, yet not nearly so large as would occur if in the sulphides all six M electrons surrounded the L-shell, while in the sulphates all six were far away and unreplaced. The separation between the $K\alpha_1$ and $K\alpha_2$ lines is also changed to a marked extent. [B. Ray, Copenhagen; Phil. Mag. *50*, pp. 505-511; 1925.] KARL K. DARROW

Effect of Cold-drawing on the Density of Tungsten.—Tungsten rods formed from powdered tungsten by powerful compression, followed by sintering and by heat-treatment, have initially a density about 12 per cent less than that (19.35) determined for compact metal by x-ray determinations of the crystal lattice. By hammering the metal so produced, its density was brought up practically to the standard value; thereafter, drawing a rod down to about .003 of its initial diameter produced no further change. The result is in discord with other published statements; the authors regard theirs as more reliable because of their method, their data being obtained by measurements of buoyancy in benzol. [W. Geiss and J. van Liempt; Ann. d. Phys. *77*, pp. 105-108; 1925.] KARL K. DARROW

EPPLEY UNSATURATED STANDARD CELLS AT HIGH TEMPERATURES

By Warren C. Vosburgh

For a test of the behavior of portable unsaturated cells at high temperatures twenty cells were selected which were well-aged and representative of Eppley cells. Ten had been made with 13% cadmium amalgam and the other ten with the usual 12.5% amalgam. The first ten were made in one lot, while the second ten consisted of one or more cells from six different lots. The cells were measured at room temperature and then were placed in an oil thermostat at 35°C. Measurements were made on two successive days, and then the temperature was

Table 1. *Electromotive forces of Eppley portable unsaturated standard cells at high temperatures*

A. *Cells with 13% amalgam*

Cells	Electromotive Force Volts.						
	22.2°C 72°F	35°C 95°F	42°C 108°F	50°C 122°F	56°C 132°F	60°C 140°F	24°C 75°F
18806	1.01890	1.01883	1.01884	1.01888	1.01893	1.01900	1.01924
7	71	66	69	75	84	1.01890	1.01901
8	87	80	81	85	91	95	1.01924
9	70	66	67	72	79	85	1.01884
10	72	69	70	75	83	89	88
11	73	67	69	74	80	85	87
12	79	72	73	77	84	88	1.01952
13	70	66	69	74	80	85	1.01881
14	77	71	74	79	87	92	1.01908
15	75	71	74	79	85	90	1.01901

raised to 42°, 50°, 56° and 60°. Measurements were made on two successive days at both 42° and 50° and on three successive days at both 56° and 60°. The two or three results at any one temperature agreed in most cases within 0.00001 volt (.001%), and in all cases within 0.00004 volt (.004%). After the third measurement at 60° the cells were cooled to room temperature and measured one day later. The results are shown in Table 1.

The results show that cells with 13% amalgam can be used up to 60°C. (140°F) without appreciable error. The cells seemed to be as constant at the high temperatures as at low and there was no indication of any harmful effect of the high temperature. Some of the cells with 12.5% amalgam, however, showed a drop in electromotive force at 56° and a still further drop at 60°, while others were as little affected as the cells with 13% amalgam. Undoubtedly the composition of the amalgam varied somewhat even in the cells of the same nominal amalgam composition. The composition of the amalgam may vary without affecting the electromotive force provided that it stays within the range for the

B. *Cells with* 12.5% *amalgam*

Cells	Electromotive Force Volts.						
	22.2°C 72°F	35°C 95°F	42°C 108°F	50°C 122°F	56°C 132°F	60°C 140°F	24°C 75°F
15753	—	1.01854	1.01856	1.01862	1.01761	1.01619	1.01883
16615	—	[illegible] 74	73	76	1.01879	1.01885	1.01923
17489	—	1.01918	1.01917	1.01920	70	1.01726	1.01944
17589	1.01846	1.01843	1.01845	1.01853	03	1.01661	1.01861
17593	72	64	66	71	23	1.01682	75
17610	84	79	80	85	35	1.01692	98
17700	64	59	61	66	73	1.01878	65
17702	56	54	56	62	70	75	55
17703	69	64	65	70	76	83	73
17704	64	60	61	66	73	79	71

coexistence at equilibrium of liquid and solid phases. If, due to a small proportion of cadmium, or to high temperature, or to both as probable in the case of some of the cells, the amalgam becomes entirely liquid, the electromotive force will vary considerably with the composition and with temperature.

Cells made with a 12½% amalgam can probably be depended upon up to about 55° for purposes not requiring a degree of accuracy greater than 0.01%. As cells grow older the proportion of cadmium in the amalgam becomes less and the maximum temperature at which they may be used without error becomes lower. Just how rapid this change is has not been determined, but it is likely that the change in two or three years would be hardly appreciable if the cell were not abused.

It is to be noticed that the final results at room temperature are in some cases considerably higher than the first ones. This is due to a lag in adjustment to equilibrium conditions, or hysteresis, after a tempera-

ture drop. As time goes on cells showing such high values decrease in electromotive force and finally attain equilibrium. If cells showing these high values are heated again to their maximum temperature before having come to equilibrium at a lower temperature, they reach equilibrium at the higher temperature immediately. Therefore cells used at a high temperature would not be affected by being cooled and reheated, but if used at the lower temperature after cooling they might be in error by 0.1%.

THE EPPLEY LABORATORY,
NEWPORT, R. I.

Luminosity Accompanying Reactions with Na Vapor.—Sodium vapor is fed into one end, one of a large number of other gases into the other end of a long heated tube; in a central sector of the tube the vapors meet and combine, and in most instances (not in all) the *D*-lines are emitted. In the particular case of the combination of Na and I_2 to form NaI, there are two adjacent regions of the tube where different processes occur; the authors seem to think that in one Na atoms and I_2 molecules collide and form NaI molecules and free iodine atoms, in the other the free iodine atoms combine directly with Na atoms. In this latter zone the D-lines are excited; the elementary process presumably is that an Na atom and an I atom combine and liberate 5.3 equivalent volts of energy, which is more than enough to put a second Na atom into the excited state; but this must happen much oftener than triple collisions (between an I atom and two separate Na atoms) should occur, which is difficult to understand.—[H. Beutler and M. Polanyi, Kaiser Wilhelm Institut Naturwiss., *13*, pp. 711-713; 1925.]

KARL K. DARROW

Demonstration-Experiment Showing Forced Vibrations of a Piezoelectric Crystal.—A long narrow rod of quartz cut with its length perpendicular to the principal axis and to one of the electrical axes is laid upon a glass plate, under a parallel glass plate about 1/2 mm above its upper side. The system is placed in rarefied air and an alternating voltage applied between the plates, of nearly the frequency of the natural longitudinal vibrations of the rod. The expansions and contractions of the rod set up variable charges upon its surface, diminishing from a maximum value in the center to zero at each end; these in turn result in luminous discharges to the upper glass plate which simulate the wave form of the vibration. By making the plates as long as the half-wave-length of an overtone of the rod, it is possible to make the wave forms of these harmonics visible.—[E. Giebe and A. Scheibe, Reichsanstalt; ZS. f. Phys., *33*, pp. 335-344; 1925.]

KARL K. DARROW

Capture and Loss of Electrons by Alpha-Particles.—It is found that when a beam of alpha-particles traverses Au, Al, Ag, Cu or mica, it soon attains an equilibrium-state in which there is a certain

proportion of singly-charged particles—a proportion dependent upon the speed of the particles, but *independent of the substance traversed*—mingled with the doubly-charged particles. A sheet of the solid substance equivalent to only a few mm of air is sufficient to impress this equilibrium-character upon the beam; but the author apparently did not find just how thick it needs to be. It is curious that the widely differing concentrations of electrons in these various substances should not affect the proportion of alpha-particles equipped with extra electrons as result of the transit. The dependence of the ratio r of doubly-charged to singly-charged particles upon speed v appears from the graph to be of the form $r=(av-b)^3$ for $v<4.10^8$, although the author prefers another formula.—[G. H. Henderson, Saskatchewan; Proc. Roy. Soc., *A 109*, pp. 157-165; 1925.] KARL K. DARROW

Spectra of Ionized Molecules.—Mecke compares the band spectrum of boron monoxide with an ensemble of three bandspectra of "carbon" (the first negative group of Deslandres, the "comet-tail" spectrum, and a third lately discovered) and notes similarities which cause him to ascribe these to ionized molecules of carbon monoxide and to announce that the structure of the spectrum of a molecule, like that of an atom, depends essentially on the number of electrons. Another such similarity is found between the negative bands of nitrogen, which Mecke ascribes to N_2^+, and the bands of CN. However, the frequencies ascribed to an ionized molecule with N electrons and nuclear charges aggregating $(N+1)e$ are not fourfold those belonging to a neutral molecule of N electrons and nuclear charges totalling Ne; they are of about the same order of magnitude. As the spectra of CN and of BO are not identical, they are clearly dependent on other things than the number of electrons and the total nuclear charge alone.—[R. Mecke, Bonn; Naturwiss., *13*, pp. 698-699; 1925.]

KARL K. DARROW

Elasticity and Plasticity of Single Crystals of Rocksalt.—Bending stresses were applied to thin strips of rocksalt by attaching partially-submerged weights at or near the center of the strip, which was supported near its ends, and varying the depth of water whereby the weights were buoyed up; the corresponding tensions in the strip are calculated by the usual formulas. Plastic deformation occurs (at stresses exceeding 200g/mm² for glowed and 500 g/mm² for not-glowed crystals), also elastic hysteresis, also "Nachwirkung," and there are unmistakable departures from Hooke's Law, especially when the stress is being diminished. Thus all the phenomena of masses of crystals reappear in the behavior of single crystals. When the surface on the convex side of a permanently bent crystal is dissolved off, the crystal straightens itself partially; when the surface on the concave side is dissolved off, it bends itself still more—thus showing the existence of internal stresses.—[M. Polanyi and G. Sachs, Kaiser Wilhelm Institut; ZS. f. Phys., *33*, p. 692-705; 1925.]

KARL K. DARROW

NEOCYANINE: A NEW SENSITIZER FOR THE INFRARED*

By M. L. Dundon, A. L. Schoen, and R. M. Briggs

Hitherto the most efficient sensitizer for the photography of the near infrared has been dicyanine.[1] With long exposures McLennan has photographed the mercury lines up to 1113.7 $m\mu$, while the strong line at 1014 $m\mu$ can very readily be photographed. When kryptocyanine was introduced in 1920[2] it was hoped that it would be possible to use it in place of dicyanine which is difficult to use and erratic in its sensitizing power[3] (possibly because it does not keep well even in a dry state). However, while kryptocyanine is by far the most powerful sensitizer known from 700 $m\mu$ to 800 $m\mu$ it was found that above 800 $m\mu$ its sensitizing power fell off very rapidly and that at 900 $m\mu$ dicyanine was much superior.[4]

In the course of the preparation of kryptocyanine, Dr. H. T. Clarke of this laboratory noticed that the condensation gave rise to a dye less soluble than kryptocyanine and which therefore separated from the solution. This dye, the chemical properties of which Dr. Clarke is discussing elsewhere, was prepared by him in a pure condition and has been tested by us as a sensitizer. It appears to be very valuable for photography in the near infrared and has been named "neocyanine."

ABSORPTION SPECTRUM

Fig. 1 shows the absorption curves of neocyanine, kryptocyanine, and dicyanine in alcoholic solution, the curves being measured on a photographic spectrophotometer using plates sensitized with neocyanine.

SENSITIZING METHODS

For sensitizing plates by bathing we have used for dicyanine A the following procedure.[5] Plates were bathed for 4 minutes at 50°F in a solution containing

*Communication No. 255 from the Research Laboratory of the Eastman Kodak Company.

[1] J. C. McLennan and W. W. Shaver, Proc. Roy. Soc. A., *100*, p. 200; 1921.

[2] E. Q. Adams and H. L. Haller, J. Amer. Chem. Soc., *42*, p. 2661; 1920.

[3] Merrill, Bull. of the Bur. of Standards, *14*, p. 489; 1918.

[4] C. E. K. Mees and G. Gutekunst, "Some New Sensitizers for the Deep Red," J. Ind. Eng. Chem., *14*, p. 1060; 1922.

[5] Due to Meggers. Walters and Davis, "Studies in Color-Sensitive Photographic Plates and Methods of Sensitizing by Bathing." Bureau of Standards Scientific Paper No. 422.

Dicyanine A 1/5000 in methyl alcohol	20 cc
Methyl Alcohol	20 cc
Ammonia (28%)	4 cc
Water	60 cc

They were then rinsed 30 seconds in methyl alcohol and dried rapidly before a fan.

With kryptocyanine good results can be obtained by bathing for 45 seconds at 50°F in a solution of 1/500,000 of kryptocyanine in water, and rinsing for 30 seconds in alcohol before drying. However, the best results are obtained by bathing first for 1 minute at 50°F in a water solution containing kryptocyanine 1/1,000,000 to which has been added just sufficient acetic acid to decolorize the solution (about two drops of glacial acetic acid per liter). This is followed by treatment

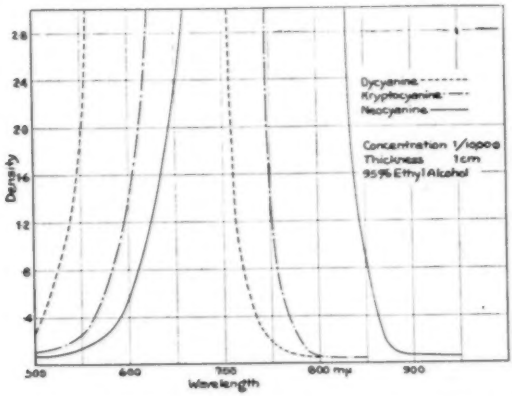

FIG. 1. *Absorption curves of alcohol solution of dicyanine, kryptocyanine, and neocyanine.*

for 1 minute in an alkali bath, such as 2% borax or 4% ammonia. The borax appears to give cleaner results with almost as good red sensitizing. A fresh stock solution of the dye 1/1000 in methyl alcohol is used. The very low concentrations employed should be noted, as higher concentrations will produce fog and decrease sensitivity. Kryptocyanine, however, can most easily be utilized by addition to the emulsion, which gives results equal to the best obtainable by bathing. Kryptocyanine plates, of great sensitiveness between 700 $m\mu$ and 800 $m\mu$ with a maximum at 760 $m\mu$, have been supplied from this laboratory for about eighteen months under the name of "Extreme Red Sensitive" plates.

With neocyanine the best results were obtained by bathing the plates for 1 minute at 50°F in a 1/200,000 solution of the dye containing

25% methyl alcohol, followed by an alcohol rinse for 30 seconds and drying as rapidly as possible.

The special sensitizing procedure used with kryptocyanine was not found advantageous, nor did any additions to the bath increase the sensitiveness. Excellent results, however, were obtained by hypersensitizing the dried plates by bathing in a 4% (by volume) solution of stronger ammonia water (28%) for 1 minute before use, using the plates wet or dry as may be most convenient.

Neocyanine was found also to give excellent results in the emulsion and we propose to supply to those who desire it either the dye itself or plates sensitized with it. These latter will be called "Infrared Sensitive" plates and when hypersensitized with ammonia are equal in sensitiveness to any we have been able to make by bathing and hypersensitizing.

SENSITIVENESS

While kryptocyanine sensitizes with a very sharp strong maximum at 760 $m\mu$, neocyanine sensitizes weakly with a broad band stretching from 700 $m\mu$ to 900 $m\mu$ and a maximum about 830 $m\mu$. In spite of its general weakness the sensitiveness above about 820 $m\mu$ is much superior to that conferred by any other sensitizer, and out to 900 $m\mu$ there is no difficulty in photographing the spectrum with short exposures. In Fig. 2 are shown comparative spectra taken with a black wedge in front of the spectroscope slit on dicyanine, kryptocyanine, and neocyanine plates using a filter cutting at 580 $m\mu$. The exposures were 5 seconds for dicyanine, 10 seconds for kryptocyanine, and 60 seconds for neocyanine. In this case the kryptocyanine and neocyanine plates were not hypersensitized. When photographing beyond 900 $m\mu$ the advantages of neocyanine over dicyanine are less marked but it is still much superior. The mercury line at 1014 $m\mu$ can be photographed with neocyanine with about 1/5 the exposure required for dicyanine, and the mercury line at 1128.8 $m\mu$ is easily photographed with long exposures. Fig. 3 shows a spectrum of the mercury arc obtained with 15 hours exposure upon Infrared Sensitive plates hypersensitized with ammonia.

In addition photographs were taken of a distant landscape including a range of hills about 20 miles away. With neocyanine plates and a combination filter[6] which limited the effective radiation to 850-900 $m\mu$, the photograph showed good contrast between wooded and open fields

[6] Wratten No. 87 filter plus a 1 cm thick solution of 1/20000 neocyanine in ethyl alcohol.

on the distant hills. With ordinary panchromatic plates and a Wratten No. 25 filter which utilized radiation between 580 and 700 $m\mu$ the intervening haze veiled the distant hills in such a way as to eliminate

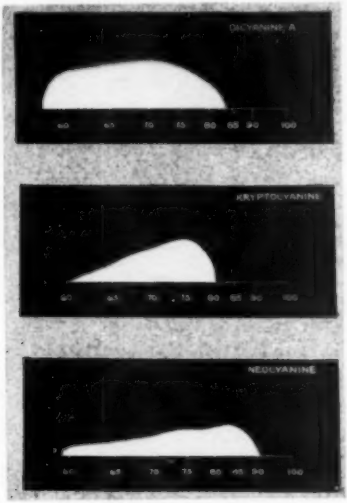

FIG. 2. *Wedge spectrograms of plates sensitized with dicyanine, kryptocyanine, and neocyanine.*

nearly all detail. While requiring a much longer exposure the Neocyanine plates show an appreciable improvement in haze cutting over kryptocyanine plates which utilize radiation from 700 to 800 $m\mu$.

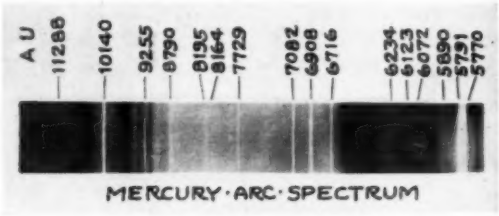

FIG. 3. *Mercury arc spectrum on a hypersensitized neocyanine plate.*

SUMMARY

A new sensitizer called "neocyanine" has been found which sensitizes more powerfully beyond 800 $m\mu$ than any dye previously reported.

EASTMAN KODAK CO.,
ROCHESTER, N. Y.,
OCTOBER, 1925.

SPECTRAL DISTRIBUTION OF SENSITIVITY OF PHOTOGRAPHIC MATERIALS*

By L. A. Jones and Otto Sandvik

A knowledge of the spectral energy sensitivity of a photographic emulsion is of considerable importance both from the practical and the theoretical points of view. Among practical problems for which a knowledge of the spectral sensitivity is necessary may be mentioned photographic spectro-photometry, relative and absolute intensity of spectrum lines, and many types of astronomical work. Several investigators have measured the amount of monochromatic radiant energy necessary to render a silver bromide grain developable. In most cases, however, the investigations have been restricted to very few lines, usually only one or two. Owing to this and the variety of experimental conditions, it would be impossible from these data to draw any conclusions regarding the sensitivity as a function of the wave length.

Leimbach[1] made a systematic study of the spectral energy sensitivity of five different emulsions in the spectral region 4500A to 7000A. He found the maximum sensitivity to occur in the spectral region corresponding to 4500A. Luckiesh, Holladay, and Taylor[2] have published sensitivity curves for four emulsions indicating a maximum sensitivity near 4500A. Otashiro[3] finds a maximum sensitivity at about 4650A, the sensitivity decreasing uniformly through the blue and violet. Helmick[4] (using an emulsion of the ordinary blue sensitive type) has measured the average number of quanta required to render a silver bromide grain developable by radiation of wave lengths 2537, 2653, 3131, 3650, and 5490. He finds that the least number of quanta per grain are required by wave length 5490 and the maximum number at 2537.

Very recently data have been published by Harrison[20] showing the relation between speed and wave length for six different photographic plates in the region between 2000A and 4500A. His results indicate that the speed is practically constant for wave lengths greater than 2500A dropping rapidly for wave lengths less than 2500A. He also shows the relation between contrast and wave length.

*Communication No. 256 from the Research Laboratory of the Eastman Kodak Company.

Work on this problem has been in progress in this laboratory for some time, some preliminary results of rather fragmentary character having been published in the preliminary communication.[21] Since then a special monochromatic sensitometer has been constructed and some further measurements have been made.

The purpose of this paper is to describe the apparatus, to outline the method of procedure, and to give the values obtained for the spectral sensitivity of four emulsions in the region from 3000A to 7000A. No attempt has been made to correct for the reciprocity failure. However, the error thus incurred is believed to be small except at 3000A.

The authors plan to study the spectral energy sensitivity for many representative emulsions throughout the entire region of sensitivity

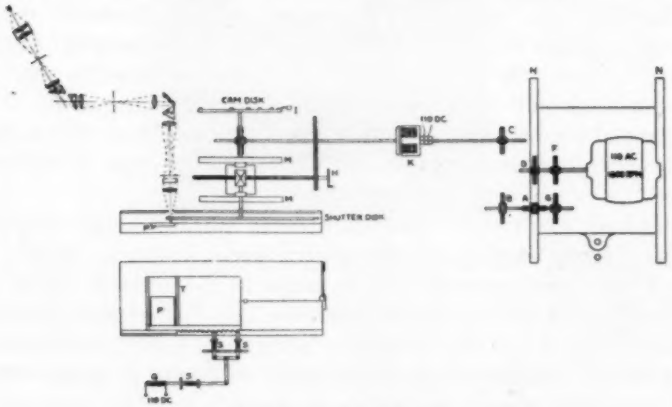

FIG. 1. *Schematic diagram of the sensitometer.*

in the visible and the ultraviolet as far as the transmission of gelatine permits.[5] In the future we hope also to investigate the so-called reciprocity failure for monochromatic radiation. Jones and Huse[6] have investigated the reciprocity failure for white light and a full treatment of the subject may be found in their papers. Parkhurst[7] has found that the exponent p in Schwarzschild's formula varies not only with the intensity, but also the color of the incident radiation.

APPARATUS

A schematic diagram of the monochromatic sensitometer is shown in Fig. 1. This consists essentially of an optical system for obtaining monochromatic radiation and a mechanical device for exposing the photographic plate to this radiation for known time intervals. On account

of the well known failure of the photographic plate to integrate an intermittent exposure it is not desirable to use sensitometers in which the variation of exposure time is obtained by the use of a rapidly rotating sector in which apertures of various angular dimensions are cut. It was decided, therefore, after a careful consideration of the merits of other possible mechanisms to adopt a rotating sector wheel of the one turn type. Sensitometers using a simple sector wheel of the one turn type are subject to the inconvenient limitation in exposure range imposed by the inability to obtain sufficiently great variation in the angular widths of the apertures. This difficulty was overcome by adopting a rotating sector in which the apertures are arranged spirally around the axis of rotation, the entire disc being moved laterally while rotating at a uniform angular velocity. The relative positions of the essential parts of this instrument are shown in Fig. 1. The shutter disc as shown is keyed to the shaft carried by a moveable bearing sliding between the ways *MM*. The rotation of the lead screw H (driven by the same shaft which imparts rotational motion to the shutter disc) moves the shutter disc laterally while it is being rotated. Mounted on the shaft carrying the shutter disc is the cam disc which carries a series of 13 cam elements. As these cam elements rotate with the cam disc they close the electrical contact, *I*, at definitely predetermined intervals. The closing of this contact energizes the solenoid, *Q*, which through a suitable escapement movement moves the photographic plate forward by one step during the time when the opaque elements of the shutter disc occupy a position in the path of the exposing radiation. By utilizing the spiral arrangement of the apertures the maximum exposure time corresponds to an angular rotation of 720° of the shutter disc. In this way 12 exposures increasing by consecutive powers of 2 are obtained, thus giving a range of exposure times from 1 to 2048. The greatest exposure range that can be obtained satisfactorily with a simple disc is 1 to 256, this limitation being that imposed by the precision obtainable in cutting slots of very small angular dimensions. In Fig. 2 is a diagram showing the shape of the shutter disc with its spirally arranged apertures. The shutter disc is driven at a constant angular velocity by means of a synchronous motor. Since photographic materials in themselves differ enormously in sensitivity it was necessary to provide a series of speed changes so as to make available a wide variation in the exposure times. For this purpose suitable reduction gears were provided. The motor with these reducing gears *A*, *D*, *F*, *G*, is mounted on a base slidable in the ways *NN*. By moving this assembly the shaft *B*

can be connected either to C or D by means of a slip collar. Likewise A can be connected to either C or D. In this way four different gear ratios are available with a resulting range of exposure times from 1/64 up to 26384 seconds. The exposing unit and the power unit are connected

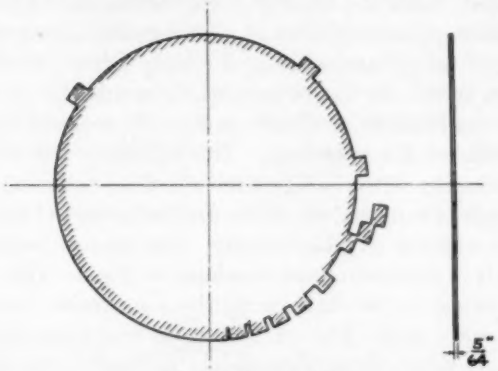

FIG. 2. *The sector disc.*

by magnetic clutch K which releases automatically when a given series of exposures is completed. The photographic plate is carried in a plate holder of proper design as shown at P. This takes a 4×5 plate, and by adjusting this plate holder vertically, several series of exposures can

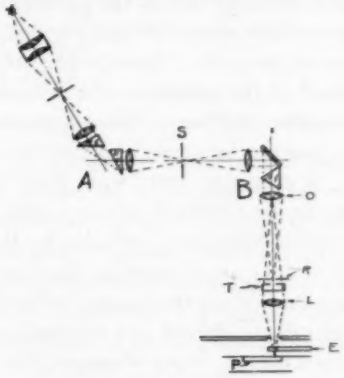

FIG. 3. *Diagram showing the optical system*

be made side by side on the same plate. The optical system used for supplying homogeneous radiation is positioned as shown in the upper left hand corner of Fig. 1, and is shown in greater detail in Fig. 3. Two monochromatic illuminators used are in series, the exit slit, S, of

instrument *A* being the entrance slit of instrument *B*. Immediately outside of the exit slit, *R*, of the second monochromatic illuminator, *B*, is located the linear thermopile which is used for measuring the energy emerging from the slit of the instrument. Immediately behind this thermopile is mounted the quartz lens *L* of such focal length that an image of the objective *O* is formed on the photographic plate *P*, the diameter of this objective is approximately 1.5 inches, while its image formed on the lens is .3 inches. In this way a small spot uniformly illuminated with homogeneous radiation is contained. The shutter disc occupied the position as shown at *E*, the opaque portions closing the aperture through which the radiation enters the sensitometer during the instant when the photographic plate is moved laterally between successive exposures. Photographs showing the complete assembly of the apparatus are reproduced in Figs. 4 and 5.

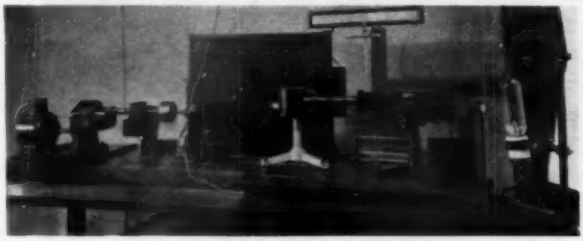

FIG. 4. *Photograph of sensitometer.*

The light source used was a tungsten ribbon filament imaged by the quartz condenser on the entrance slit of the monochromatic illuminator *A*, which is a quartz instrument obtained from the Bausch and Lomb Optical Co. The second instrument *B* is a Hilger constant deviation quartz monochromatic illuminator having an aperture ratio of *F*: 8 which is somewhat less than instrument *A*. A Hilger linear thermopile having a resistance of 12.5 ohms in connection with a Leeds and Northrup galvanometer having a voltage sensitivity of 11.1 mm deflection per microvolt on a scale at 1 meter was used for measuring the energy.

The apparatus was located in a building whose top floor is occupied by heavy machinery. We therefore had considerable difficulty in finding a suitable galvanometer support. The one finally adopted was a Leeds and Northrup type Julius suspension with additional conico-

helical spiral springs[8] placed in the suspension cables of the galvanometer support. This support was found to be extremely effective, the galvanometer deflection, due to mechanical vibration, was too small to be observed on a scale two meters distant from the galvanometer.

Since the sensivitity of the galvanometer was insufficient to measure energy in the ultraviolet we had to resort to Wien's law to determine energy in that region. For this reason it was very essential to have the two spectrometers set so that the wave length at the center of the slit of each was the same. First, each instrument was carefully adjusted so that the drum settings indicated the correct wave length within the limit of accuracy of observation. Using very narrow slits the first

FIG. 5. *Photograph of sensitometer and galvanometer support.*

monochromator was set to read the wave length desired, turning the wave length drum of the second monochromator a few angstroms at the time and obtaining an exposure for each setting. On developing these, a series of images would result, only one of which was centrally located with respect to the telescope slit of the second monochromator. The wave length setting corresponding to this centrally located image was used.

It was desirable that both the exposure times and the slit widths be a minimum. A combination was chosen so as to include the entire straight line portion of the characteristic curves.

The development was made in a process developer at 68°F.

Elon	1 gram
Hydrochinon	9 "
Sodium sulphite	75 "
Potassium carbonate	25 "
Potassium bromide	5 "
Water to	1000 cc

Each set of plates was developed to four different gammas, the second of which was approximately unity. The plates were fixed in acid hypo for ten minutes and washed in running water for about thirty minutes.

It may be well at this point to discuss briefly the question of spectral impurities and the necessity for using two monochromatic illuminators in series. In the original design of this sensitometer a single monochromatic illuminator was used, but due to the presence in the radiation emerging from the exit slit of wave lengths other than that indicated by the wave length drum setting, it was found impossible to obtain satisfactory results. The detection of this spectral impurity was due largely to the type of optical system used. Referring again to Fig. 3 it will be noted that the lens *L* placed just outside of the slit of the monochromatic illuminator is used to image the objective *O* on the photographic plate. With all optical parts properly adjusted and performing perfectly, this should give on the photographic plate an area uniformly illuminated with radiation of a homogeneity dependent upon the slit widths and other optical constants of the apparatus. A photographic plate exposed under these conditions should therefore yield a small round spot of uniform density. When our preliminary exposures were made this was found to be the case throughout the wave length region where the product of energy by spectral sensitivity of the photographic material was relatively high. In regions where this product was relatively low, however, these images were found to be nonuniform and filled with small lines and markings of unknown origin. A careful analysis of the results indicated that these markings were due to radiation of wave length other than that which should have been present. We believe that they were due chiefly to out-of-focus slit images formed by light reflected and re-reflected from the lens and prism surfaces. Attempts were made to eliminate these impurities by means of filters, diaphragms, etc., but no entirely satisfactory method was found. It was therefore decided to place a second monochromatic illuminator in series with the first. This was done and the difficulty disappeared completely. Fig. 6 shows the way in which these stray radiations appear in the

developed images. Groups *A* and *B* were obtained with the Hilger monochromator and C and D with the Bausch and Lomb instrument. *A* and *D* were made using the tungsten filament lamp as a source, and *B* and *C* with the mercury arc. It will be noted that using the tungsten lamp at wave lengths 4000A and 5000A there is no visible nonuniformity due to the presence of these impurities. At other wave lengths, however, they become very evident. In some cases the magnitude of this stray radiation amounts to at least 50% of the total radiation present. If the lens, *L*, had not been used, and the radiation after passing through the slit had been allowed to fall on the plate, or had the slit *R* been imaged on the photographic plate, these impurities would not have caused any nonuniformity in the deposit and hence might not have been discovered. Many workers in this field have used the direct slit images and we feel that there is a great possibility that some of the work done is subject to unsuspected error due to impurities in the monochromatic radiation. Group *E* in Fig. 6 was obtained with the Hilger instrument using a tungsten lamp screened with Wratten No. 2 and K-2 filters. These filters absorb all radiation of wave length shorter than 4000A. This indicates that the stray radiation causing the trouble is of wave length longer than 4000A. The wave length settings represented in group *E* are, reading from left to right, 2000A, 2500A, 3000A, and 3500A. There was still the possibility, however, that the very small amount of short wave radiation transmitted by the filters mentioned might have produced under these conditions an exposure sufficient to give the images. Accordingly exposures were made at 3500A (Fig. 6, f) without a filter, with a No. 18 (ultraviolet), with a K-2, and finally with a No. 18 and K-2 together. The results show conclusively that a large percentage of the stray radiation is of wave length longer than 4000A.

The diffuse densities of the silver deposits of a set of six sensitometric strips, for each wave length, and each time of development, were measured on the Jones' densitometer. The fog correction applied to a given density was of the form suggested by R. B. Wilsey.[10] He assumes that the fog over any image is proportional to the mass of silver unaffected by the exposure, and is given by the equation

$$D_f = \frac{D_m - D_\infty}{D_m} \cdot F \qquad (1)$$

where F is the fog density in an unexposed area, D_m the maximum density developable and D_∞ the density which would be given by com-

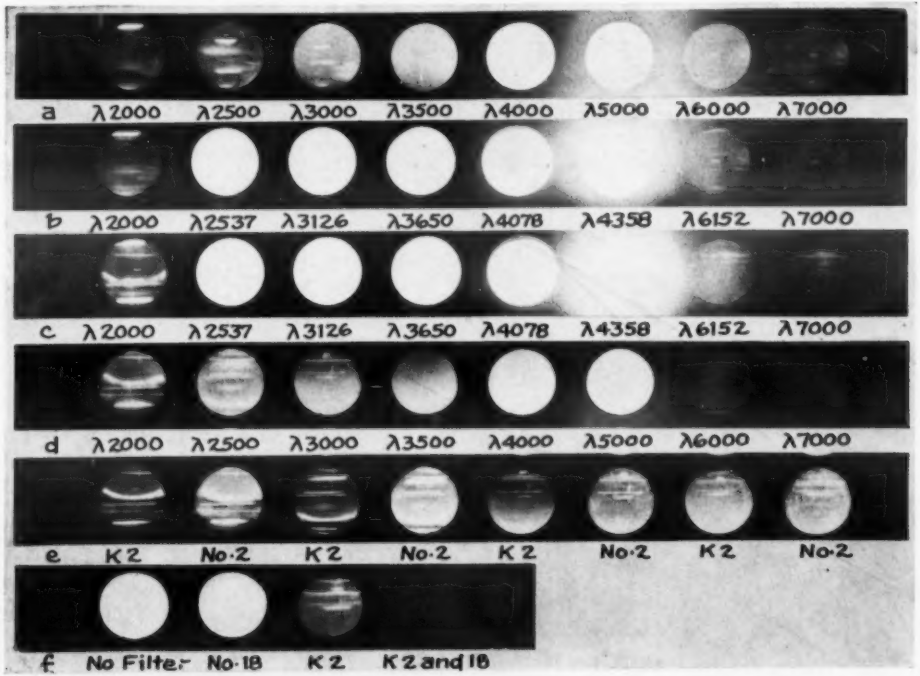

FIG. 6. *Enlarged images showing spectral impurities obtained by using a single monochromator.*

plete development of the exposed area being considered. D_f is the fog correction to be applied to any particular density. Plotting the values of density, corrected according to the above formula, against log E for each wave length, a family of characteristic curves for different times of development was obtained.

Speed of a photographic emulsion has been defined by Hurter and Driffield[11] as the reciprocal of the inertia, or the reciprocal of the inertia multiplied by an integer, where the inertia is the E value at the point where the straight line portion of the characteristic curve intersects the log E axis. Suppose that we have a family of characteristic curves, obtained by increasing the time of development. Now, if the straight portion of these curves have a common intersection point, and that point lies on the log E axis, then the inertia point, and hence the speed, will not change with gamma, that is, with the time of development. The failure of the former of the above conditions would make the second impossible. Hence we shall confine our discussion only to the case of a common intersection. That this is the only case has been established by the experiments of Hurter and Driffield,[12] Sheppard and Mees,[13] and by Nietz.[14] Moreover when no soluble bromides are present during the development the intersection point remains on the log E axis. If, however, soluble bromides are present, either in the plate or the developer, the straight portions meet below the log E axis. Nietz has shown that for a given developer the amount of depression is proportional to the quantity of soluble bromides present. The position of the intersection point is also affected by soluble bromides formed during development, and accordingly, by the amount of stirring which the developer receives. The change of inertia, and hence speed, thus incurred is a very important point which is frequently overlooked by workers in photographic sensitivity. The procedure adopted by the authors was to locate the point of intersection, and from this point to draw a line of unit slope which served to locate the inertia point or the exposure necessary to produce a silver deposit of unit density, say, when developed to a gamma of unity.

The thermopile was calibrated in place behind the spectrometer slit by means of a Hefner lamp. According to Coblentz[15] if a diaphragm 14 by 50 mm is placed in front of the Hefner flame at a distance of 10 cm, the intensity of total radiation at a distance of 1 meter from the flame is 232×10^{-6} calorie per square centimeter per second. Since the deflections were proportional to the intensity, the energy flux for a given deflection could be calculated.

As stated above, lack of galvanometer sensitivity prevented experimental evaluation of the energy flux at 3000A and 3500A. The distribution of energy emitted by a tungsten ribbon operating at a color temperature T_c^0K and a true temperature T^0K was calculated by means of Wien's equation where the radiant flux, I_r,

$$I_\lambda = \epsilon C_1 \lambda^{-5} e^{-C_2/\lambda T} \tag{2}$$

the value of ϵ, the emissivity of tungsten, was obtained from the data of Worthing[16] and Hulburt,[17] and from the empirical equation by Luckiesh, Holladay and Taylor[18],

$$\epsilon_\lambda = \frac{0.45}{\lambda^{0.2}} - \frac{25}{10^6} T \tag{3}$$

The color temperature of the lamp was redetermined at frequent intervals.

In order to check the agreement between the calculated and the observed values of the energy in ergs per square centimeter per second incident on the photographic plate, the values were computed by Wien's equation for several wave lengths whose intensity had been measured with the thermopile. The values obtained by the two methods are compared in Table 1.

TABLE 1.

Wave length	$I_{calc.}$	$I_{obs.}$
3000	0.026	——
3500	0.48	——
4000	3.1	3.3
4500	12	11
5000	28	26
5500	48	48
6000	93	90
6500	121	116
7000	176	176

In order to find the relative amount of energy, E, incident on the photographic plate it was necessary to know the amount of light lost by reflection at the lens and prism surfaces. The per cent reflected at each lens surface was calculated by means of Frenel's law of reflection for normal incidence. The value of μ used was for the ordinary ray.

$$R = \left(\frac{\mu - 1}{\mu + 1}\right)^2 \tag{4}$$

The reflection from each prism surface was calculated by the Frenels equation

$$R = \tfrac{1}{2}\frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)} \tag{5}$$

where i and r are respectively the angles of incidence and reflection; absorption was considered negligible. The absolute values of the energy flux at 3000A and 3500A were obtained by multiplying the measured energy flux at 5500A by the computed energy ratios for the respective wave lengths. Now if I_s is the energy flux through the slit, the energy I incident per second, per unit area, of the plate is

$$I_p = \frac{I_s\left[(1-2)\left(\frac{\mu-1}{\mu+1}\right)^2\right]}{A} \tag{6}$$

where A is the area of the image.

From the family of characteristic curves we obtain the exposure time, t, required to produce a silver deposit of unit density for unit gamma.

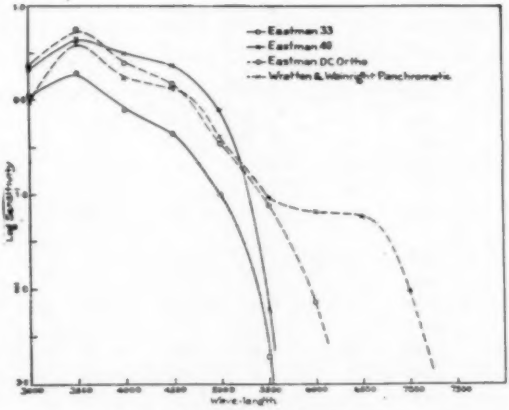

FIG. 7. *Sensitivity wave length curves.*

The value of $I \cdot t$ is directly proportional to the inertia as defined above; but the sensitivity, S, has been defined as the reciprocal of the inertia, hence, omitting the constant of proportionality

$$s = 1/I \cdot t \tag{7}$$

and $\log S = \log 1 - \log I \cdot t$.

RESULTS

The values of log S and its variation with wave length are shown in Table 2 and Fig. 7. These results differ from the results of all previous observers with the exception of Harrison (loc. cit.) in that the maximum sensitivity occurs in the ultraviolet. The real significance of the sudden drop below 3500A is somewhat doubtful, but probably can be attributed to reciprocity failure. This point will be investigated more fully in the near future when we plan to use a radiant source of much greater intensity.

TABLE 2. Emulsions 1, 2, 3, and 4 are Eastman 33, No. 1420; Eastman 40, No. 1172; Eastman D. C. Orthochromatic No. 1615; and W. and W. Panchromatic No. 4066. γ_{max} are the values of gamma for maximum time of development. I is the energy in ergs per square centimeter per second incident on the photographic plate. E is the product of I, the intensity, and t, the time of exposure. S is the sensitivity. K is the velocity constant of development.

Emulsion	λ	I	E	log S	S	γ_{max}	K
1	3000	0.026	0.90	0.048	1.1	1.30	0.24
	3500	0.48	0.53	0.275	1.9	1.66	0.14
	4000	3.3	1.3	$\bar{1}$.890	0.77	1.96	0.13
	4500	11	2.3	$\bar{1}$.638	0.43	2.31	0.12
	5000	26	10	$\bar{2}$.998	0.099	2.61	0.10
	5500	48	51	$\bar{3}$.289	0.0019	2.94	0.10
2	3000	0.026	0.47	0.324	2.1	1.41	0.15
	3500	0.48	0.23	0.645	4.4	1.70	0.12
	4000	3.3	0.33	0.480	3.0	1.86	0.10
	4500	11	0.43	0.371	2.4	1.94	0.074
	5000	26	1.3	$\bar{1}$.893	0.78	2.00	0.074
	5500	48	160	$\bar{3}$.799	0.0063	2.38	0.074
3	3000	0.026	0.43	0.366	2.3	1.39	0.11
	3500	0.48	0.18	0.755	5.7	1.43	0.10
	4000	3.3	0.41	0.390	2.5	1.71	0.079
	4500	11	0.67	0.176	1.5	2.15	0.073
	5000	26	2.9	$\bar{1}$.544	0.35	2.16	0.083
	5500	48	8.3	$\bar{1}$.082	0.11	2.54	0.078
	6000	90	134	$\bar{3}$.871	0.0074	3.00	0.068
4	3000	0.026	1.1	$\bar{1}$.971	0.93	0.96	0.21
	3500	0.48	0.24	0.610	4.1	1.15	0.14
	4000	3.3	0.59	0.230	1.7	1.66	0.094
	4500	11	0.74	0.128	1.3	2.05	0.070
	5000	26	2.5	$\bar{1}$.608	0.41	2.48	0.058
	5500	48	11	$\bar{2}$.969	0.093	3.08	0.067
	6000	90	15	$\bar{2}$.823	0.067	2.90	0.073
	6500	116	17	$\bar{2}$.761	0.058	3.38	0.064
	7000	176	97	$\bar{2}$.014	0.010	3.27	0.067

Table 2 and Figs. 8, 9, 10, and 11 show the change in gamma with time of development and with the wave lengths. These results are in a general way similar to those of other observers, except Leimbach,[19]

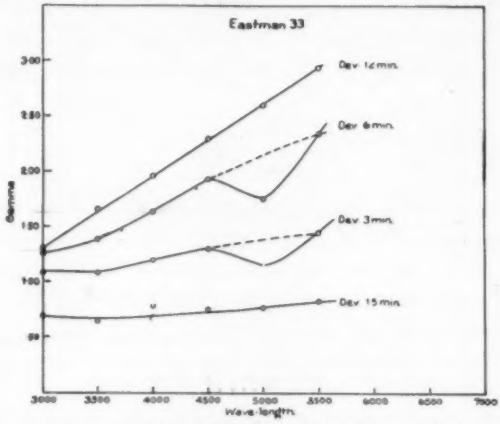

FIG. 8. *Gamma wave length curves for different times of development.*

who finds that the gamma does not change with the wave lengths. His conclusions are probably based on very short times of development, in which case the gamma is approximately the same for all wave lengths.

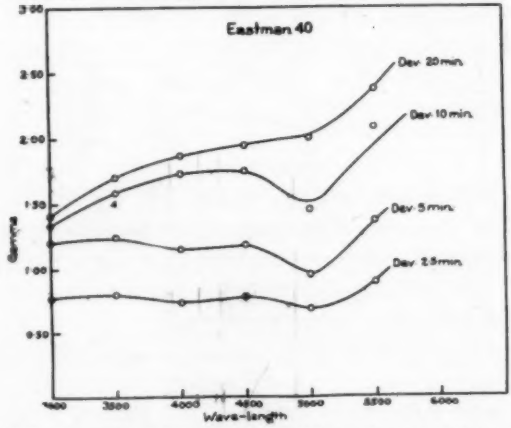

FIG. 9. *Gamma wave length curves for different times of development.*

This is just what one would expect if the grains near the surface start to develop first. It is interesting to note that the gamma wave length curves become nearly straight lines for long development. The decrease

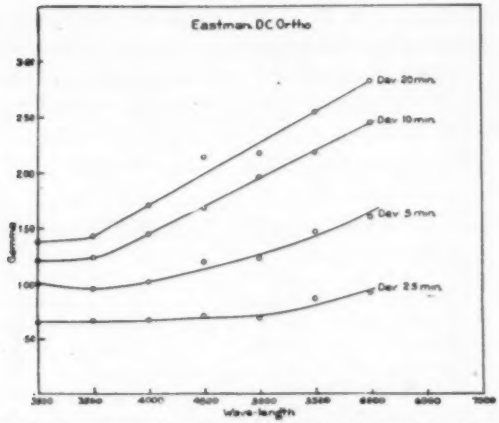

FIG. 10. *Gamma wave length curves for different times of development.*

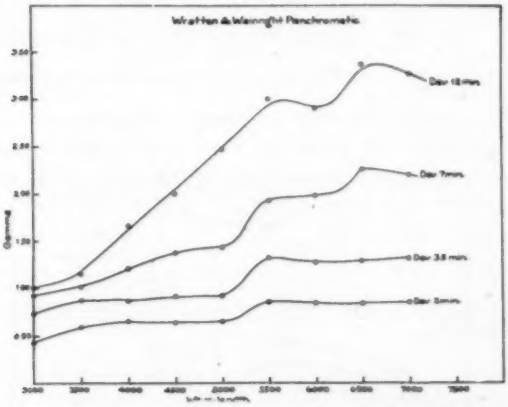

FIG. 11. *Gamma wave length curves for different times of development.*

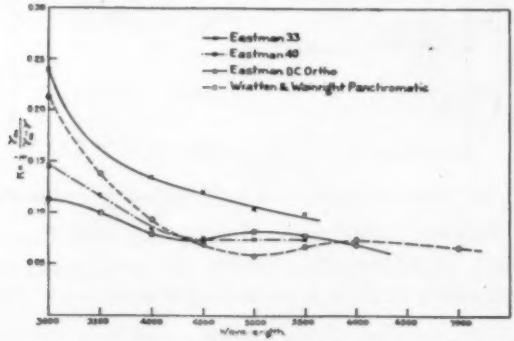

FIG. 12. *Change in the velocity of development with wave length.*

in gamma at 5000A has not yet been explained; it is probably connected with the absorption in that region.

It is of interest to see whether the development of the latent image proceeds at the same rate for all wave lengths. By assuming that the γ corresponding to the longest time of development is nearly equal to γ_∞, we may calculate the velocity constant, K, by means of the Sheppard and Mees equation

$$K = \frac{1}{t} \log \frac{\gamma_\infty}{\gamma_\infty - \gamma} \tag{8}$$

where t is the time development required to produce a given value of gamma. The computed values of K are given in Table 2 and Fig. 12. It will be observed that its value decreases generally towards the red end of the spectrum. One would expect, since the latent image, due to absorption of the ultraviolet radiation, is located near the surface, that its rate of development would be relatively higher than of a latent image produced by visible radiation. However, in the absence of quantitative measurements on the rate of absorption of the radiation by the emulsion it is difficult to say how much of the change in the rate of development can be attributed to penetration of the latent image into the emulsion.

R. B. Wilsey (loc. cit.) working with white light and x-rays has shown that the penetration of the developer into the emulsion is very rapid and that the depth of the latent image has no appreciable effect on the rate at which it develops. The large values of K in the ultraviolet region may be attributed largely to a change in the function representing the course of development.

CONCLUSIONS

Two monochromatic illuminators in series were used to reduce the per cent of stray radiation to a minimum.

The results of the investigation on spectral distribution of sensitivity show the maximum sensitivity to occur in the ultraviolet.

Gamma increases with the wave length in the spectral region investigated; and the increase becomes more marked for longer times of development.

The maximum gamma is a minimum in the ultraviolet, increasing generally towards the red end of the spectrum. K, on the other hand, varies in the opposite direction.

EASTMAN KODAK CO.,
ROCHESTER, N. Y.,
OCTOBER, 1925.

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